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MASTER THESIS

Analysis of additive manufacturing in the aeronautical field

Barbara Cabrera Agudo

SUPERVISED BY

Miguel Valero García

Universitat Politècnica de Catalunya
Master in Aerospace Science & Technology
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BY

Barbara Cabrera Agudo

DIPLOMA THESIS FOR DEGREE

Master in Aerospace Science and Technology

AT

Universitat Politècnica de Catalunya

SUPERVISED BY:

Miguel Valero García
Arquitectura de Computadors

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ABSTRACT

Additive manufacturing is a new technology that is currently implemented in different industries such as oil, gas, automation and the medical industry. The objective of this thesis is to analyse whether 3D printing will be suitable for use in the aeronautical field, specifically, within the airlines. Throughout the different chapters this thesis will analyse this technology and will carry out a practical case study. This case study will focus on seatbelts, it will study different factors such as traditional manufacturing, (which is currently the manufacturing technique), additive manufacturing and the economical impact of changing to an alternative manufacturing method. The changes to the industry´s dynamic from utilising a different manufacturing process and the repercussions from this change will also be taken into account in this study.

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GLOSSARY

- 3DP: 3D Printing
- ABS: Acrylonitrile Betadiene Styrene
- Al: Aluminium
- AM: Additive Manufacturing
- ATM: Air Traffic Management
- CAGR: Compound Annual Growth Rate
- EASA: European Aviation Safety Agency
- EY: Ernst & Young
- FAA: Federal Aviation Administration
- FDM: Fused Deposition Modelling
- Fe: Iron
- FFF: Fused Filament Fabrication
- GE: General Electric
- HDPE: High Density Polyethylene
- IMA: Integrated Modular Avionics
- LOM: Digital Light Processing
- PA 6/6: Nylon 6/6
- PBT: Polybutylene Tereph thallate
- PC: Polycarbonate
- PET: Polyethylene Terephthalate
- PLA: Polylactic acid or Polylactide
- PMMA: Acrylic, General Purpose, Model
- POM: Acetal Homopolymer Unreinforced
- PP: Plaster – Based 3DP
- PP: Polypropylene
- PS: Polystyrene
- SAE: Society of Automotive Engineers
- SIB: Safety Information Bulletin
- SLA: Stereo Lithography Apparatus
- SLM: Selective Laser Melting
- SLS: Selective Laser Selective
- R&D: Research and Development
- Ti: Titanium
- TM: Traditional Manufacturing
- TSO: Technical Standard Order
- TSO: Technical Standard Order
- UTS: tensile stress

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INTRODUCTION

In this day and age, the implementation of new technology that offers new improvements can be appreciated in any production process. One such example is car manufacturing; as the majority of this process is completely automatic as a result of using new technology (the use of robots, artificial intelligence) to assist factory mechanics. This thesis will carry out a study which will take into account the new technology such is additive manufacturing[1] and will apply it to the aeronautical field, specifically, to how it would effect to the airlines. The reasons why this technology should be utilised in respect to other disruptive technologies[2] are because with additive manufacturing, assembly will be not required. As a result, the lead-time[3] would be reduced, the models or products would be able to be customized and the waste would also be reduced. In the aeronautical field there is more research about the improvements that can be made to materials that are applied in aircraft everyday. The reason additive manufacturing is best suited to the aeronautical field is that this technology allows the customization of materials, in order to obtain the most suitable mechanical and physical properties. This is incredible for airlines as their goal of airlines moving forward is to reduce the weight of the aircraft, with additive manufacturing the weight of individual components would be able to be decreased. This is due to the reduction of the pieces, therefore eliminating the requirement for assembly, but without reducing the safety or the efficiency of the aircraft. This thesis will be a study to predict the future or possible changes of the supply chain within the aeronautical industry.

The thesis will be organized into five distinct chapters. The first chapter will introduce additive manufacturing and will define it as a method of production. It will also give an overview of the diverse printers that exist in the market and the different materials that can be used with them. The second chapter will examine research about new trends in the aeronautical field and it will demonstrate how additive manufacturing is a very important part of these trends. The third chapter will analyse the additive manufacturing in different industries as well as the future potential of this technology and the evolution of 3D printing[4] within the aeronautical field. The fourth chapter will study which pieces are the best to produce with 3DP. The fifth chapter make a practical case in which

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[2] Disruptive technologies is an innovation the creates a new market and value network and eventually disrupts an existing market and value network, displacing established market-leading firms, products and alliances. Some examples about disruptive technologies are internet of things, robots, drones, additive manufacturing, artificial intelligence, virtual reality, blockchain…

[3] Lead-time is the latency between the initiation and execution of a process. For example, the lead-time between the placement of an order and delivery of a new car from a manufacturer may be anywhere from 2 weeks to 6 months. In industry, lead time reduction is an important part of lean manufacturing and lean construction

[4] 3D printing has the same meaning than additive manufacturing. Henceforth Additive Manufacturing and 3D printing will be applied to the in the same context.

aircraft seatbelts will be analysed for use with additive manufacturing. It will also investigate the impact of any potential change in manufacturing methods for the airlines. Finally, the last chapter will address conclusions about the findings obtained in this thesis and will obtain an estimation as to the suitability of additive manufacturing in this industry.

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Chapter 1

INTRODUCTION TO ADDITIVE MANUFACTURING

The use of additive manufacturing technologies in different industries has increased substantially during the past 20 years. Currently, additive manufacturing (AM) enables and facilitates the production of moderate to mass quantities of products that can be customized individually. This technology is opening new opportunities in terms of the production paradigm and manufacturing possibilities. This chapter is going to explain the real meaning of this technology for the different industries concerned, as well as types of 3D printers and the new materials that are trending currently in this technology [1].

1.1. What is Additive Manufacturing?

Additive manufacturing is an alternative to the traditional product manufacturing process through which three-dimensional (3-D) solid objects are created. It enables the creation of physical 3-D models of objects using a series of additive or layered development frameworks, where layers are laid down in succession to create a complete 3-D object, in other words, additive manufacturing is the same as 3D printing (3DP) [2].

1.2. Types of 3D printers

Currently the 3D printing industry is still maturing and is still in a very early stage of development. Nowadays there are just over ten types of printing technology and according to the process that it is used, it will use one material or another will be used. The types of printing technology are outlined below [3]:

- Fused Deposition Modelling (FDM)
- Laminated Object Manufacturing (LOM)
- Digital Light Processing (DLP)
- Stereolithography(SLA)
- Plaster-based 3D Printing (PP)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Electronic Beam Melting (EBM)

1.2.1. Fused Deposition Modelling (FDM)

Fused deposition modelling (FDM) technology was developed and implemented at first by Scott Crump, the founder Stratasys Ltd., in 1980. Other 3D printing companies have adopted similar technologies but under different names. A well-known company nowadays known as MarkerBot coined a nearly identical technology known as Fused Filament Fabrication (FFF) [3].

FDM builds parts up layer-by-layer by heating and extruding thermoplastic filament. It is ideal for building durable components with complex geometries in nearly any shape and size. Figure 1 shows the FDM printer in which the support material spool (blue) and build material spool (grey) can be seen. In this figure it can be seen how objects are built up in parts layer-by-layer with the extrusion head. When the object is finished the support material is then discarded. FDM also creates parts and prototypes with outstanding thermal and chemical resistance, as well as excellent strength-to-weight ratios. This technology has a lot of benefits, like design freedom, it can build complex parts with the same tried and tested thermoplastics found in conventional manufacturing. It offers a wide range of durable thermoplastics with unique characteristics making it ideal for many industries, such as the medical industry, because it is biocompatible and transparent. FDM has also been an improvement for the transportation industries to improve the strength and heat resistance of parts and components. Other advantages are the low maintenance cost and that it can produce thin parts and produce them very fast.

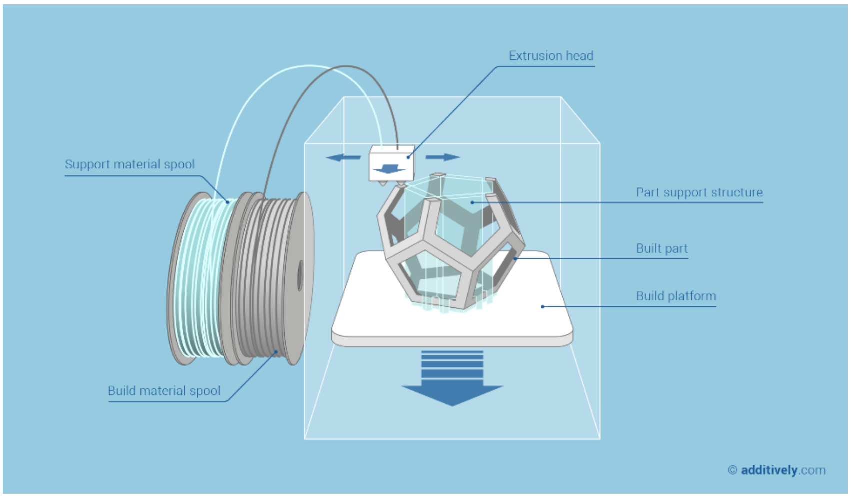


Figure 1. Fused Deposition Modelling Process

1.2.2. Laminated Object Manufacturing (LOM)

Laminated object manufacturing (LOM) is a rapid prototyping system that was developed by the California-based company, Helisys INC [3].

During the LOM process, layers of adhesive-coated paper, plastic or metal laminates are fused together using heat and pressure and then cut into shape with a computer controlled laser or knife. Figure 2 below shows the process in which the sheet is adhered to a substrate with the heated roller. After the laser traces the desired dimensions of the prototype, the laser cross hatches the non-part areas in order to facilitate waste removal. The last step of process is the movement of the platform lowering into a new position to receive the next laser and the process is repeated until the full model or prototype is prepared. Post-processing of 3D printed parts includes steps such as machining and drilling. LOM is probably not the most popular 3D printing method but one of the most affordable and fastest. The cost of printing is low due to raw materials not being expensive. Objects printed with LOM can be relatively big, that means that no chemical reaction is needed to print large parts.

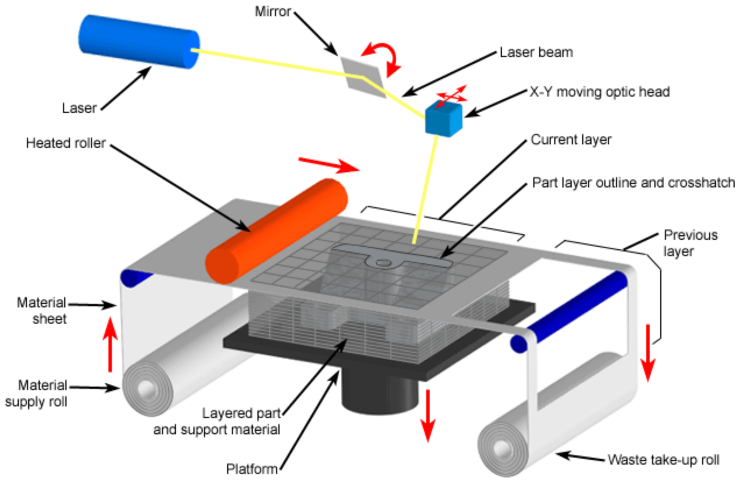


Figure 2. Laminated Object Manufacturing Process

1.2.3. Digital Light Processing (DLP)

Digital light processing is another 3D printing process very similar to stereolithography. It was created in 1987 by Larry Hornbeck of Texas Instruments and became very popular in Projector production [3].

The DPL works with a vat of liquid polymer that is exposed to light from a DLP projector under safelight conditions. The DLP projector displays the image of the 3D model onto the liquid polymer such is shown in Figure 3, the exposed liquid polymer hardens as the built plate moves down and the liquid polymer is once more exposed to light. The process is repeated until the 3D model is complete and the vat is drained of liquid, revealing the solidified model. DLP 3D printing is a faster method and can print objects with a higher resolution.

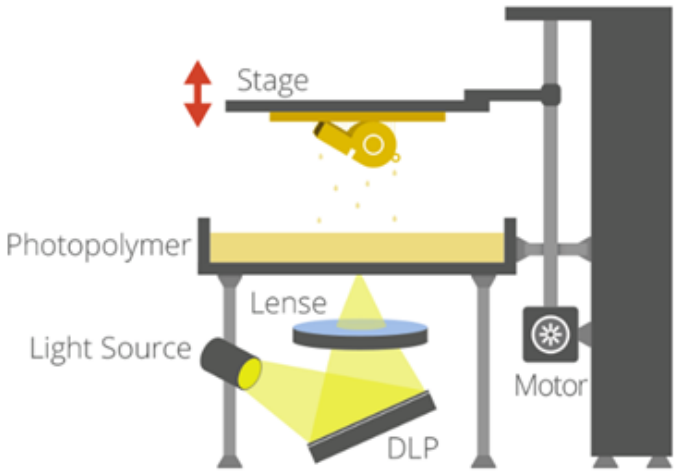


Figure 3. Digital Light Processing Process

1.2.4. Stereo Lithography Apparatus (SLA)

Stereolithography is a 3D printing method, the oldest one in the history of AM and is still in use nowadays. This method was patented by Charles Hull, co-founder of 3D Systems, Inc in 1986. The process of printing involves a uniquely designed 3D printing machine called a stereo lithograph apparatus (SLA), which converts liquid plastic into solid 3D objects [3].

SLA printing machines does not work like typical desktop printers which extrude some amount of ink onto the surface. SLA 3D printers work with excess liquid plastic that after some time hardens and forms into a solid object. Figure 4 demonstrates the process of building pieces through the use of excess liquid. Parts built with 3D printers of this type usually have smooth surfaces but their quality very much depends, because this method is inconsistent. Stereolithography is widely used in prototyping as it doesn't require too much time to produce an object and its cost is relatively cheap compared to other means of prototyping.

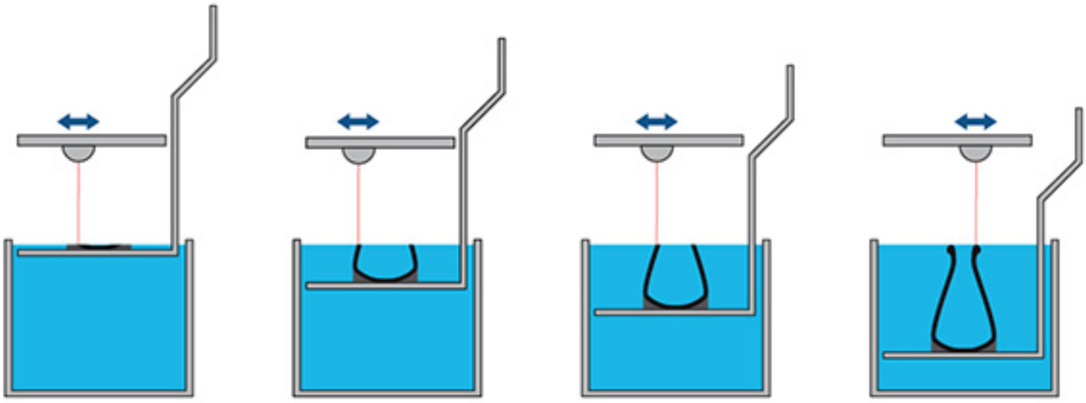


Figure 4. Stereo Lithography Apparatus (SLA)

1.2.5. Plaster-based 3D Printing (PP)

Plaster-based is also known as binder jetting. This process uses two materials (Figure 5 displays both the support material and build material), and powder material binder [3]. The binder acts are used as an adhesive between layers, this is usually in liquid form and the build material in powder form. The process is a print that is made by a plane milling head which moves horizontally along the x and y axis of the machine and deposits alternating layers of the build material and the binding material (the component is built with the inkjet print heads, shown in Figure 5). After each layer, the object being printed is lowered on its build platform. The problem with this method is that the material characteristics are not always suitable for structural parts, despite the relative speed of printing.

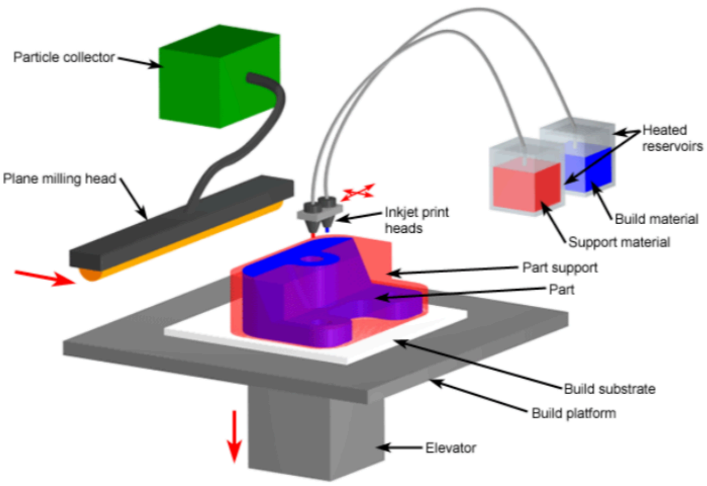


Figure 5. Plaster-based 3D Printing

1.2.6. Selective Laser Sintering (SLS)

Selective laser sintering is a technique that uses a laser as the power source to sinter powdered material, typically nylon/polyamide, by aiming the laser automatically at points in space defined by a 3D model, binding the material together to create a solid structure, such as the one that is displayed in Figure 6 [3].

Some SLS machines use single-component powder, such as in direct metal laser sintering (powders are commonly produced by ball milling). However, most SLS machines use two-component powders, typically either coated powder or a powder mixture. In single-component powders, the laser melts only the outer surface of the particles (surface melting), fusing the solid non-melted cores to each other and to the previous layer. The diverse lasers that are utilised in this process are shown below in Figure 6.

This technology has a lot of advantages, such as having a good chemical resistance, as the parts possess high strength and stiffness. It can also construct complex parts with interior components, channels and can be built without trapping the material inside or altering the surface after the support removal. SLS is the fastest additive manufacturing process for printing functional, durable, prototypes or end user parts.

The only disadvantage of SLS is that printed parts have surface porosity, but applying a sealant such as cyanoacrylate to the surface can seal the porosity.

1.2.7. Selective Laser Melting (SLM)

Selective laser melting is a technique designed that uses a high power-density laser to melt and fuse metallic powders together. By many academics, SLM is considered to be a subcategory of SLS. SLM proves that 3D printing has the ability to fully melt metal material into a solid 3D-dimensional part unlike SLS [3].

There is one main difference between SLS and SLM. SLS is the process able to be applied to a variety of materials such as plastics, glass, ceramic whilst SLM can only be used to fully melt metal, meaning the powder is not being fused together but actually liquefied long enough to melt the powder grains into a homogeneous part. The materials that usually are used in SLM are copper, tool steel, cobalt chrome, titanium, tungsten, aluminium, stainless steel and gold. SLM can produce stronger parts because of its reduced porosity and greater control over crystal structure, which helps prevent part failure. However, SLM is only feasible when using a single metal powder. Figure 6 shows the process, which is identical to SLS as only the materials that utilised are different.

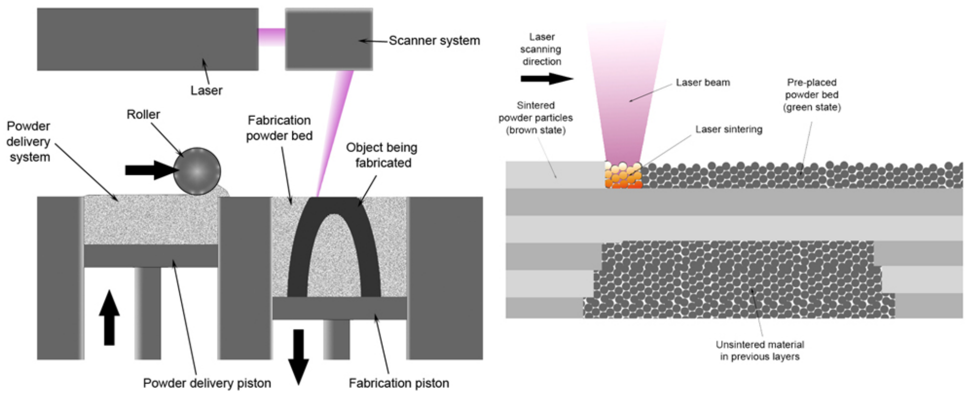


Figure 6. Selective Laser Sintering and Melting

1.2.8. Electron Beam Melting (EBM)

Electron beam melting is a type of additive manufacturing used for metal parts [2.8 (1)]. It is similar to laser melting, but works with an electron beam instead of a laser. The raw material (metal powder or wire) is placed under a vacuum and fused together via heating from an electron beam (shown in Figure 7). In other words, the machine distributes a layer of metal powder onto a build platform, which is then melted by the electronic beam. The build platform is then lowered and the next layer of metal powder is coated on top. The process of coating powder and melting where needed is repeated and the parts are built up layer by layer in the powder bed.

This technology manufactures parts in standard metal with high density and good mechanical properties. The areas of application are small series parts, one of kind parts, prototypes and support parts that can be produced directly by electron beam melting (EBM).

According to different investigations by the company General Electric (GE) the materials that are currently being used in EBM are titanium and its different alloys, cobalt chrome, steel and nickel alloys such as Inconel 718. These are some examples of metals referred to as super alloys within the aeronautical industry. The areas of application where these alloys are typically applied are turbine blades, impeller pumps for aerospace, turbocharger wheels in the automotive industry and implants in medical engineering.

As with every manufacturing process, there are advantages and disadvantages when creating objects using EBM. The advantages are the following:

- No additional auxiliary equipment needed
- Increased efficiency in raw material use
- Significantly reduced amount of time to finish operations
- Freedom in design- “design for function”
- Processing of high-melting and/or highly reactive materials
- Decreased lead times for design and fabrication, shorter time-to-market
- High degree of component customization

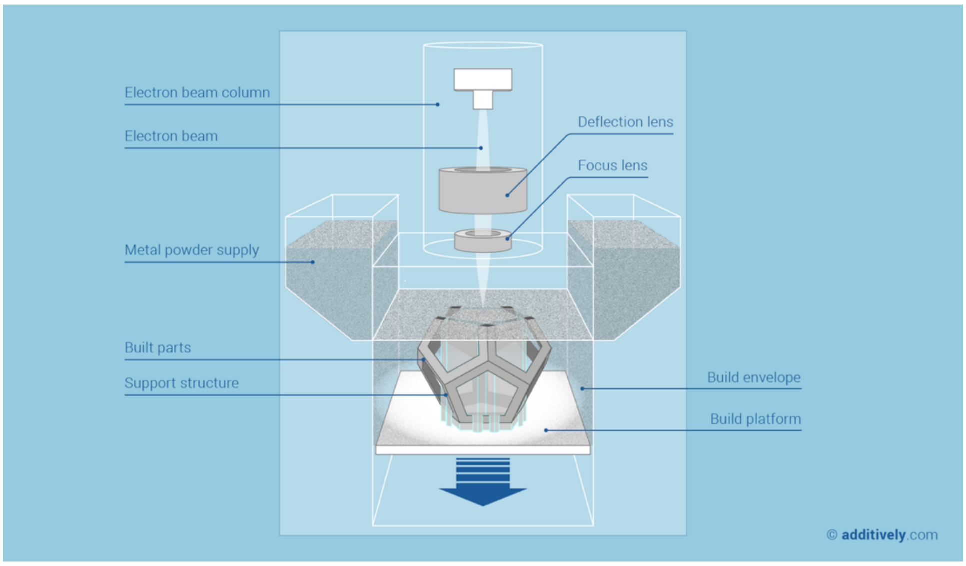


Figure 7. Electron Beam Melting (EBM)

Shown in the following table (Table 1) are some advantages of the 3DP types that have been described above:

SORT	DESCRIPTION	ADVANTAGES
FDM	Fused Desposition Modeling	Simple, cheap, it is the most popular
LOM	Laminated Object Manufacturing	Rapid prototyping technology
DLP	Digital Light Processing	High Precision
SLA	Stereo Lithography Apparatus	Rapid manufacturing large tool
PP	Plaster-based 3D Printing	Low cost
SLS	Selective Laser Sintering	Stronger structure
SLM	Selective Laser Melting	Replacing welding processes
EBM	Electronic Beam Melting	Reduces residual stress

Table 1. Advantages Summary for 3DP Types

1.3. 3D Printing Materials

The materials available for 3D printing have come a long way since the early days of the technology. There are now a wide variety of different material types, which are supplied in different states (powder, filament, pellets, granules, resin, etc) [5,6].

Specific materials are now generally developed for specific platforms performing dedicated applications (an example would be the dental sector) with material properties that more precisely suit their application.

However, there are now so many property materials from the many different 3D printer vendors that it would be impossible to be able to cover them all here. According to a leading market report publisher *MarketsantMarkets* [7], the 3D printing materials segment is going to reach $1.052 billion in global turnover by 2019. It is estimated that the materials market is going to grow at a compound annual growth rate (CAGR) [8] of 20.4%, given that the current 3D printing materials market value is around $400 million.

1.3.1. Plastics

Nylon, or Polyamide, is commonly used in powder form with the sintering process or in filament form with the FDM process. It is a strong, flexible and durable plastic material that has proved reliable for 3D printing. It is naturally white in colour but it can be coloured. This material can also be combined with powdered aluminium (if the plastic is in powdered format as well) to produce another common 3DP material for sintering known as the Alumide.

ABS is another common plastic used for 3D printing, and is widely used on the entry-level FDM 3D printers in filament form. It is a particularly strong plastic and comes in a wide range of colours. ABS can be bought in filament form from a number of non-proprietary sources, which is another reason why it is so popular.

PLA is a bio-degradabale plastic material that has gained traction with 3DP for this very reason. It can be utilized in resin format for DLP/SLS/SLM processes as well as in filament form for the FDM process. It is also offered in a variety of colour. The problem with this material is that it is not as durable or as flexible as ABS.

LayWood is a specially developed 3DP material for entry-level extrusion 3D printers. It comes in filament form and is a wood/polymer composite (also referred to as WPC).

1.3.2. Metals

A growing number of metals and metal composites are used for industrial grade 3D printing. Two of the most common are **aluminium and cobalt derivatives**.

One of the strongest and therefore most commonly used metals for 3D printing is **Stainless Steel** in powder form for the sintering/melting/EBM processes. It is naturally silver, but can be plated with other materials to give it a gold or bronze effect.

In the last couple of years **Gold and Silver** have been added to the range of metal materials that can be 3D printed directly, with obvious applications across the jewellery sector. These are both very strong materials and are also processed in powder form.

Titanium is one of the strongest possible metal materials and has been used for 3D printing industrial applications for some time. Supplied in powder form, it can be used for the sintering/melting/EBM processes.

1.3.3. Ceramics

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. It is important to note with these materials is that, post printing, the ceramic parts need to undergo the same processes as any ceramic part made using traditional methods of production, namely, **firing and glazing**.

1.3.4. Paper

Standard A4 copier paper is a 3D printing material employed by the proprietary selective deposition lamination (SDL) process supplied by Mcor Technologies. The company operates a notably different business model to other 3D printing vendors, whereby the capital outlay for the machine is in the mid-range, but the emphasis is very much on an easily obtainable, cost-effective material supply, that can be bought locally. 3D printed models made with paper are safe, environmentally friendly, easily recyclable and require no post-processing.

1.3.5. Biomaterials

Currently there is a huge amount of research being conducted into the potential of 3D printing biomaterials for medical applications between other applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external issues for replacement body parts.

1.3.6. Food

The food is another field that is investigated to utilize 3D printing technology, this field has increased dramatically over the last couple of years. Some examples that are been very common to print, are: **chocolate**, **sugar, pasta and meat**.

1.3.7. Other

One company that does have a unique (proprietary) material offering is Stratasys, with its digital materials for the Objet Connex 3D printing platform. This offering means that standard Object 3D printing materials can be combined during the printing process — in various and specified concentrations — to form new materials with the required properties. Up to 140 different Digital Materials can be realized from combining the existing primary materials in different ways.

Chapter 2

TRENDS IN THE AERONAUTICAL FIELD

The chapter 2 will examine the present and future progression of the aeronautical field. The aeronautical industry remains very attentive to new developments; applications or new technologies that may improve performance as well as reduce costs. The aeronautical industry has had a high increase in rising passenger traffic, accelerated equipment replacement cycles, decreasing crude oil prices, and an increase in defence spending. As a result, aeronautical manufacturers are on pace for record production levels of next generation aircraft [9].

Regarding the *2016 Global aerospace and defence sector outlook*, the global aerospace and defence industry revenues have increased 3,4% in 2017, and the 2017 FAA forecast predicts that U.S. carrier passenger growth will average 2,1 % per year for the next 20 years [14]. Finally, an estimated 1,420 large commercial aircraft will be produced, 40,5% more than five years ago in 2016 according to *Brothers, E. 2017 Aerospace Forecast [5].*

2.1. Present and Future challenges in aeronautical field

Aircraft have had a spectacular evolution in terms of aeronautics over the last few decades. Aeronautical industries from Europe and America have designed, developed and manufactured new models of air transport for civil and military aviation [12]. In the subsonic and sonic ranges for air transport, outstanding progress has been made in both the global conception of the design of aircraft based on innovative technologies.

The research made in the aeronautical field has been focused into three main branches [13]:

- Flying Safely and Simply
- Flying Economically and Efficiently
- Flying Green

The research has resulted in permitted performances; more optimized aerodynamic profiles, weight reduction, fuel savings, and the reduction of the environmental impact (emission, noise) as well as operating cost. The most significant innovations have been derived from military requirements.

Airbus carried out a conference about *Environmental Improvements today and tomorrow* [13] in which they set environmental R&T targets for the company. For 2020, they set a target for -50% CO_2, -80% NO_x and -50% noise. The goal for 2050, known as the company Flight Path, will be about -75% CO_2, -90% NO_x and -65% noise. This data is compared to the best in service technology in 2000 (displayed in the Figure 8.

Aeronautical Challenges: 2000 to 2050). To obtain these results Airbus will utilise innovative technologies.

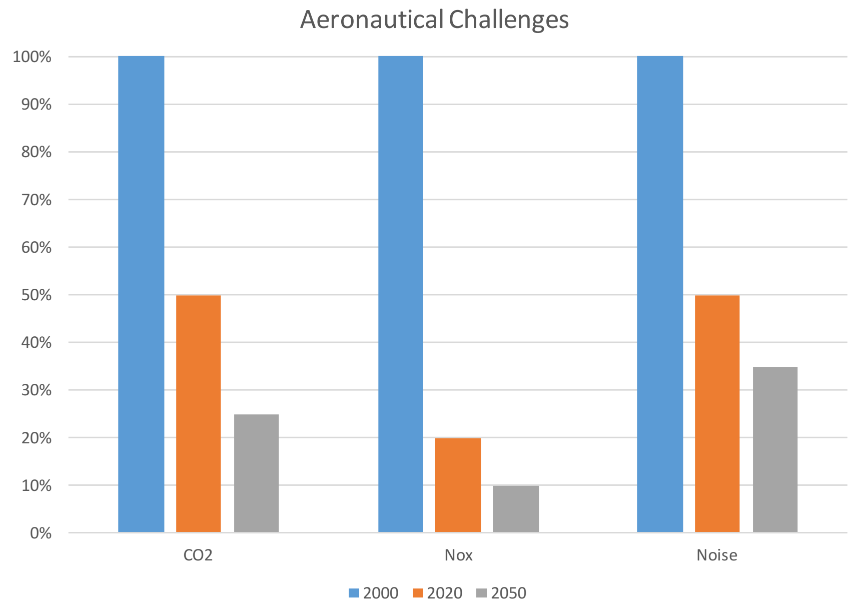


Figure 8. Aeronautical Challenges: 2000 to 2050

Many efforts in research and development have been focused on increasing the maximum range, speed and ceiling of aircraft (the rate at which an aircraft gains altitude). The Concorde was a revolutionary design that obtained a supersonic range and was one of the fastest civil aircraft in operation ever. The problem was its environmental impact; this was one reason why this service was stopped. Figure 9 demonstrates the comparison of Concorde with other aircraft. Concorde used 146,000 Pounds of fuel and with a capacity of 110 passengers; in contrast Boing 747 has three times more passengers (375 passengers) and uses approximately the same fuel as Concorde [12].

Aircraft	*Passenger Capacity*	*Fuel*	
		Pounds	*Gallons*
Boeing 707-300	145	95,500	13,071
DC-8-61	200	94,500	13,500
Boeing 747	375	170,000	24,285
DC-10	250	98,000	14,000
Concorde	110	146,000	20,857

Figure 9. Comparison between diverse aircraft

Nowadays the airbus A-380 [12], which is a subsonic aircraft, has demonstrated the level of performance that engineers and researchers are capable of supplying to its customer base and as a result, its economy, from both the technical and practical points of view.

2.2. Airbus research and technology

Airbus is a European multinational corporation that designs, manufactures and sells civil and military aeronautical products worldwide. Airbus and Boeing have been characterised as a duopoly in the large jet airliner market since the 1990s. This resulted from a series of mergers within the global aerospace industry. Nowadays, Airbus invests more than 2 billion in research and development (R&D) every year [13]. According to this data, Airbus is a good reference for identifying new trends in the aeronautical field.

The Airbus product vision is to obtain innovative new aircraft models with new concepts or improve cost and efficiency of the current models. The first stage has been implemented since 2010 and will continue until 2030 [13]. The long-term activities of Airbus (Figure 10) will be answering to new needs and the improvement of new models by applying disruptive technologies.

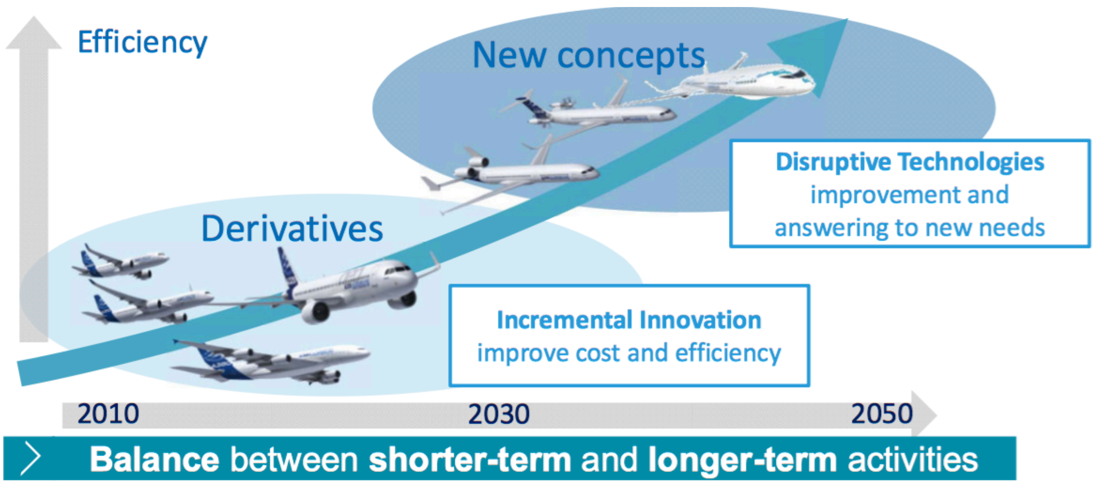


Figure 10. Technologies & Future Trends of Airbus

The technologies that have been investigated by Airbus are the following (see Figure 11 for time scale):

- <u>**New Engines**</u>**:** With these Airbus will be able to obtain the best results and better environmental effects.
  - Nowadays **Turbofan** has been dramatically improved. The noise of the turbofan has been decreased and its efficiency has increased. CO2 and NOx Emissions have also been decreased. The reason for this is that the fan size has been increased and this is producing better results (Seeing Figure 12)
  - Counter Rotating Open Rotor (**CROR**) is a new engine that will be implemented in the A-340. This engine is being realized with the help of Clean Sky. It is the largest European research programme developing innovative, cutting-edge technology aimed at reducing CO2, gas emissions and noise levels produced by an aircraft.

  - Incorporating engines with **hybrid propulsion.** As aforementioned, it is very important to reduce gas emissions and CO2. Airbus believes that the hybrid engine will be a solution for long-term pollution and it will be obtained approximately 2050.
- **Aerodynamic Efficiency:** The objective of aerodynamic efficiency is to reduce drag and noise as well as laminar and turbulent flow reduction. If these goals are achieved then the fuel consumption, gas emissions and CO2 will also be reduced.
  - **Sharklet** is a wingtip device that is implemented in the majority of aircraft nowadays. This device improves the efficiency of fix-wing aircraft by reducing drag.
  - **Riblets** are a small surface protrusions aligned with the flow of air, which add an anisotropic toughness to a surface. This surface reduces the skin friction in turbulent boundary layers. According to the graph of Figure 11, this technology will be implemented in 2020.
- **Improvements to Aircraft Structures through simulation software (capabilities):** In order for Airbus to introduce new models of aircraft into the market, it is imperative to use different simulation technology to test them before they can be cleared for use. This technology is thorough simulation software, which provide more innovative and realistic simulations every day. According to Figure 11 in approximately 2040 it will be possible to virtually design aircraft with more details than are currently available.
- **More Efficient Operation:** The airport capacity depends on the efficient operation of the airport in terms of air traffic and aircraft management. To increase this efficiency in the airport, Airbus has implemented an effective system of **air traffic management** (**ATM**). For the future, Airbus also proposes **innovative cockpits** and new models of **formations flights**.
- **Avionic and System**
  - **E-Taxi: More electrical aircraft:** It is an electric taxiing system which allows aircraft to taxi and pushback without requiring the use of aircraft engines, and is designed to reduce fuel volumes used by aircraft and therefore reducing greenhouse gas emissions during ground operations. Nowadays it is only incorporated into some models of Airbus.
  - **Integrated Modular Avionics 2^{nd}:** Integrated modular avionics (IMA) are real-time computer network airborne systems. This network consists of a number of computing modules capable of supporting numerous applications of differing levels of importance. The second generation of IMA incorporates new properties that allows business aviation to meet the future challenges. The IMA approach has three main advantages. The first advantage is the reduction of weight through a smaller number of physical components being reduced, thereby increasing fuel efficiency. The second advantage is lower maintenance by reducing the number of different types of replacement units needed to keep in stock. The third is the reduction of development costs by the provision of a standardised operating system. The aircraft models that the technology is being incorporated into are the A-350, A380 and A340M.

- **Alternative Energy:** One of the main problems in aircraft is the fuel that is used and its carbon footprint. This has a high environmental impact; the solution is to find a clean source of energy. Nowadays there are a lot of investigations and research about new sources of energy.
    - **Biofuels:** This fuel type is considered by some to be the primary means by which the aviation industry can reduce its carbon footprint. Since 2011 biofuels are being used by some airlines such as KLM, Lufthansa and Finnair.
    - **Fuel Cells:** This system is regarded as a promising solution for future electrical energy generation on board of commercial aircraft. The efficiency of the fuel cells can be improved by the production of usable water from the reaction in the fuel cells. This water can be used for on-board purposes and provide additional functions such as inserting (proving a non-inflammable atmosphere) for the jet fuel. According to the Airbus graph it will be able to implemented around 2030.
- **Innovative Structure:** The goal of the majority of aircraft manufacturees is to reduce the weight of aircraft in order to invest this weight in more speed or to improve airplane capacity.
    - **Additive Manufacturing:** AM is being implemented in the new designs of the Airbus A350 XWB and spare parts in the Airbus A310. Regarding the Figure 13, with this technology the total material will be reduced by 90% and the cost and weight of the material will also decrease by 30%. According to Figure 11 the total implementation of AM will be approximately 2020, in other words, with AM, Airbus has a futuristic technology that it will totally implement in its aircraft for innovative structures.
- **Industrialization:** Airbus has implemented different methods to improve the supply chain of factories constructing various components through investing in an automatic process.
- **Cabin and Cargo**
    - **Enhanced outside view:** According to Airbus [4] the objective of this company is that around 2050 the windows of their aircraft will have a better shape and increased width. The aim of this improvement is so that the passenger would be able to enjoy the views of the flight more.

Figure 11. New Technologies in Airbus

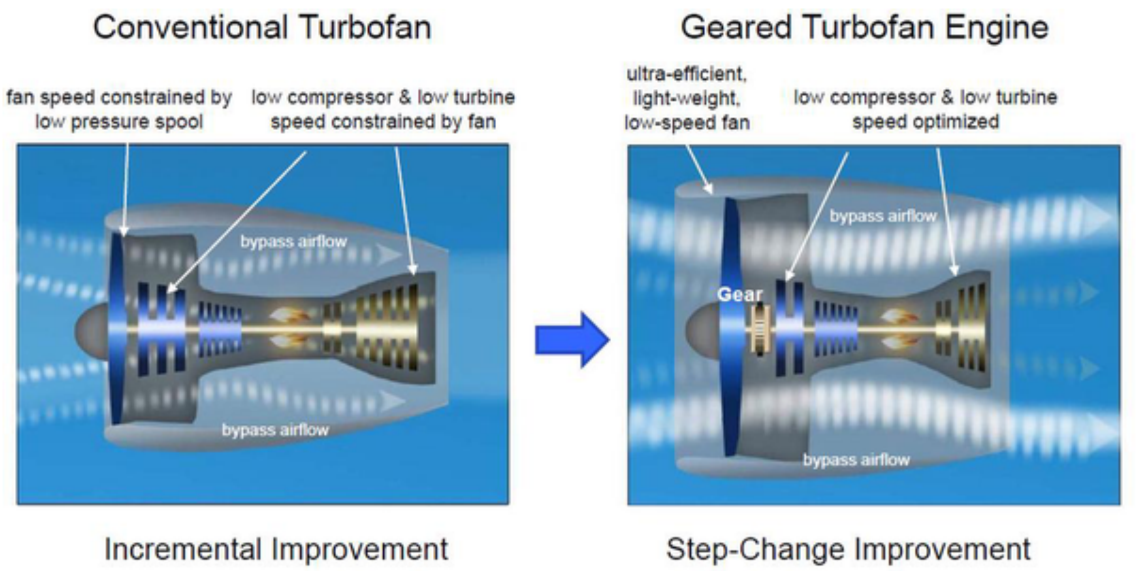


Figure 12. Conventional vs Geared Turbofan Engine

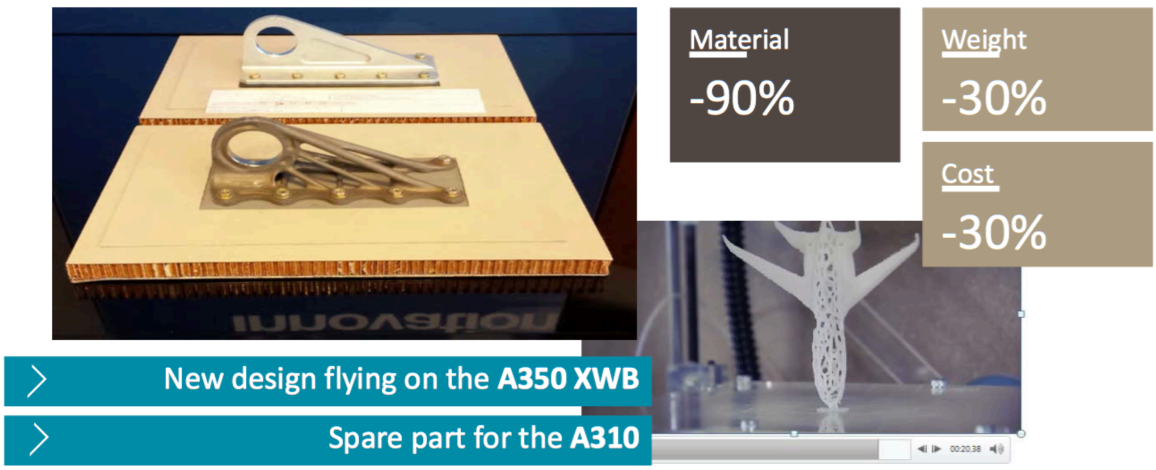


Figure 13. Implementation of AM in Airbus

2.3. Boeing research and technology

In the case of Airbus, information about the trends that will be implemented now and in the future were available to be obtained for this study, however the trends of Boeing were not available for analysis. Boeing Reach´s annual expenditure was available [1,65] for this area (presented in Figure 14). This report consists of the expenditures involved in experimentation design, development and related test activities for defence systems. It also addresses new and aircraft derived from jet aircraft including both commercial and military advanced space and other company-sponsored product development. In particular, in R&D, in 2017 more than $3,00 M [14] was invested. Boeing can be considered as more conservative in its release of information than Airbus as this gives only a relative idea of the expenditure of this research but not which specific type of trend will be invested in.

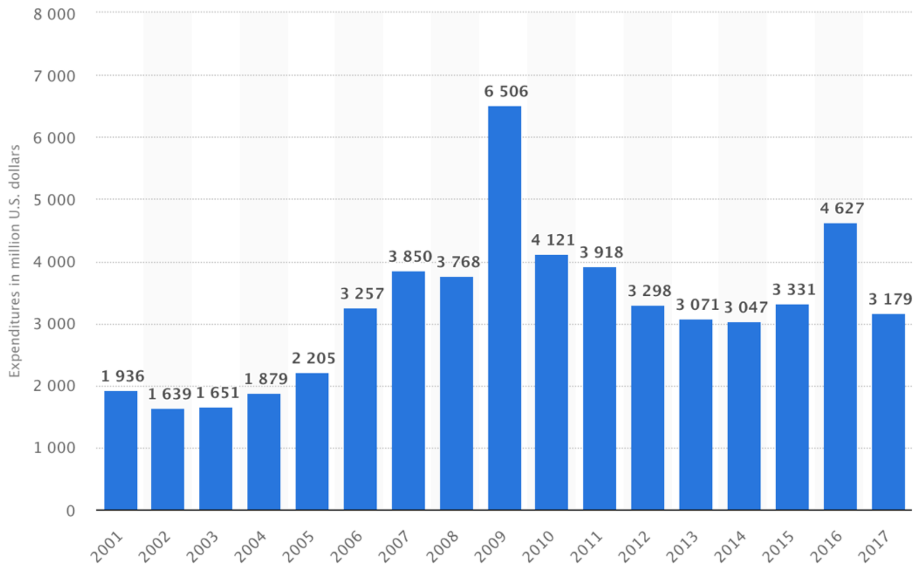


Figure 14. Expenditure of Boeing's R&D

Chapter 3

EVOLUTION OF THE ADDITIVE MANUFACTURING

This chapter will outline how this technology is evolving in diverse aspects such as revenue, emergency technologies and different industries. The maturation level of AM will also be examined.

3.1. Worldwide Revenue Evolution over time of AM

As mentioned above in chapter one, the use of additive manufacturing has increased during the last 20 years in different industries [1]. In order to show this increase a graph has been elaborated demonstrating the worldwide revenue of AM since 2012 to the projection in 2020, according to *Wohlers Associates Inc [15]* (see Figure 15. Worldwide Revenue from AM). According to the graph below in 2012 the global market for additive manufacturing products and services grew 28,6 % (CAGR) to $2.204 billion. In 2014, the AM market grew until 34,9 % (CAGR) to $ 3,07 billion. It grew another 21,7 % (CAGR) to $6,6063 billion in 2016. According to the estimations of *Wohler Associates inc [15]* the revenue is expected to increase in this year up to $12,08 billion and to exceed $21 billion by 2020.

Figure 15. Worldwide Revenue from AM

The reasons why AM has been highly increased in its usage are because it has created new opportunities in terms of production paradigms and manufacturing possibilities. In other words, AM improves the manufacturing lead time [18] that is the latency between the initiation and execution of a process amongst its other properties. An example of another property that AM allows for would be rapid prototyping, as a consequence, worldwide revenue increases each year. This was one of the first applications of the technology.

3.2. Expectations vs Time in reference to AM

Even though the worldwide revenue from AM increases more each day, AM is not a technology that is completely implemented. The degree of maturation degree of AM is the main problem for companies regarding the implementation of this technology.

There are some researchers and companies, such as Garther, which study the maturation degree by comparing this technology with other emerging technologies. Garther designed a Gartner's Hype Cycle that [16] has five different steps for categorise trends that are:

- On the rise
- At the peak of inflated expectation
- Sliding down the trough of disillusionment
- Climbing the slope of enlightenment
- Entering the plateau of productivity

The Figure 16 shows a prognostic that was created in 2014 about the progress degree of different emerging technologies whereby 3D printing technology has a high expectation, specifically in consumer 3D printing [16]. Applications that are related to AM are shown in red outlines in the graph below. The first that is shown in the graph is 3D Bio printing Systems, which is is an innovation trigger that will plateau in 5 to 10 years, according to Gartner. 3Dynamic Systems Ltd is a company, which is specialising in 3D Bio printing Systems and has developed different applications. The second 3D printing application that is shown is consumer 3D printing which is on the top of the peak of inflated expectation with the emerging technologies and whose plateau level will be reached in 5 to 10 years as well. The applications that will achieve stability before (2 to 5 years) will be Enterprise 3D printing and 3D Scanners. The prediction of this graph was estimated in 2014, nowadays there is already enterprise 3D printing and 3D scanners but the latter is not found trending with emerging technologies in 2017 [16].

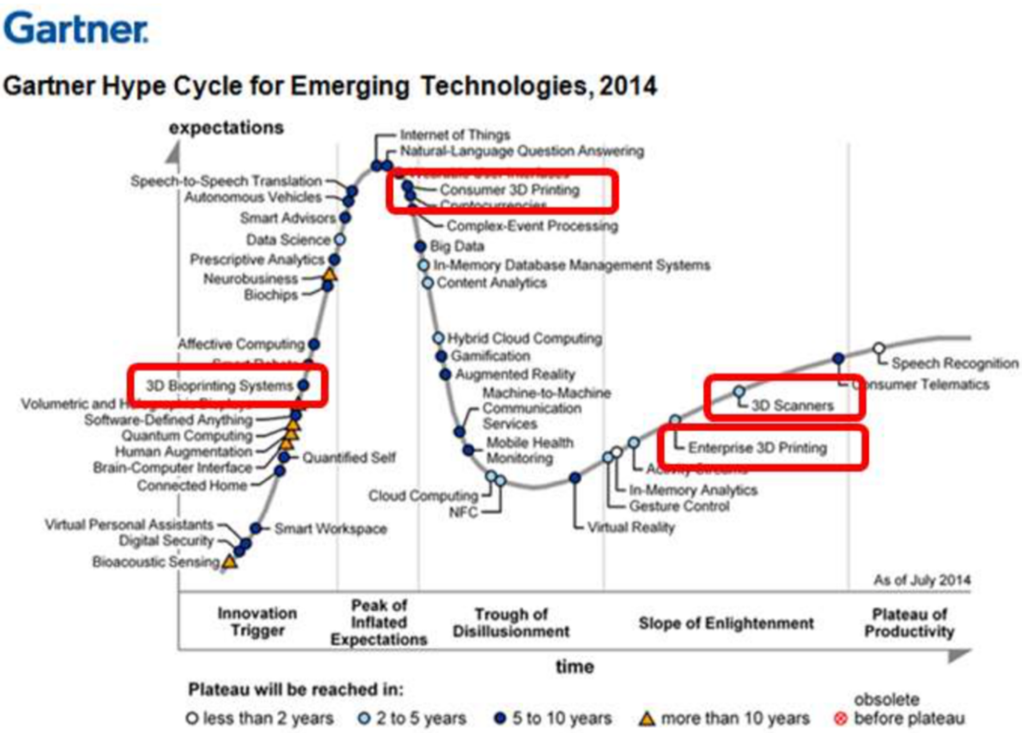


Figure 16. Gartner Hype Cycle for Emerging Technologies

Once 3D printing has been analysed as an emerging technology that could be implemented in a short time, it is then going to be analysed utilising the Gartner Hype Cycle focussing in the annual study of 2017 [16]. This can be seen in the Figure 17. Gartner Hype Cycle for 3D Printing, specifically in the main 3D printing trends. According to the graph, the applications with greater expectations are:

- Industrial 3D Printing: Plateau will be reached in 5 to 10 years
- 3D Printing in Supply Chain: Plateau will be reached in 5 to 10 years
- 3D Printing of Medical Devices: Plateau will be reached in 2 to 5 years
- 3D Printing in Manufacturing Operations: Plateau will be reached in 5 to 10 years
- Consumer 3D Printing: Plateau will be reached in 5 to 10 years

The application which is the most notable regarding the development demonstrated in the Gartner Hype Cycle is the 3D Printing in Supply Chain. This allows the aeronautical industry to be studied. The following chapter will study different cases to prove if AM is a suitable option for implementation within the aeronautical industry and how it could change the industry´s supply chain. According to this graph, AM would be a good option for the supply chain and the time until it plateaus would be short.

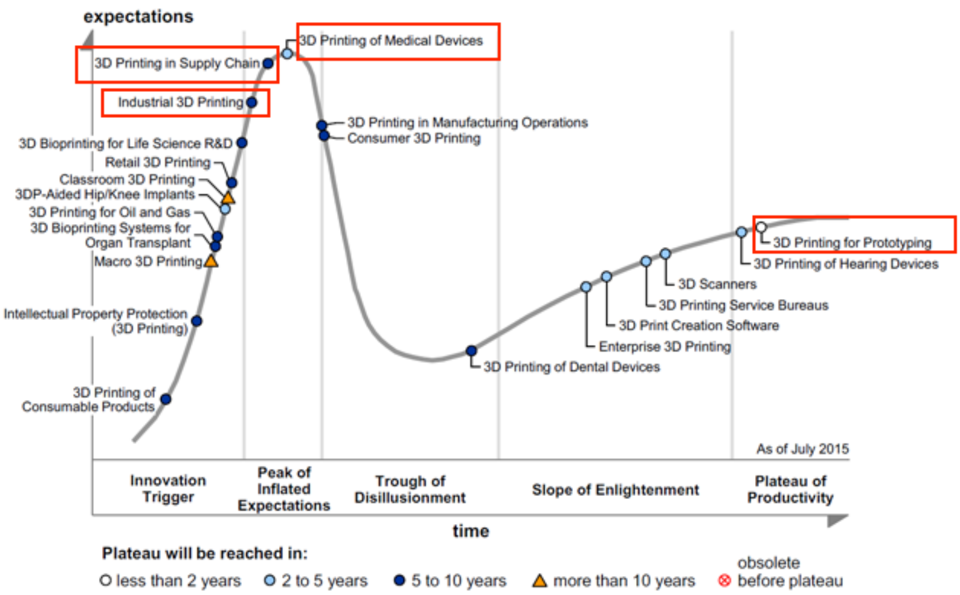


Figure 17. Gartner Hype Cycle for 3D Printing

3.3. Future Potential of 3D printing by industry

The aim of this section is to deliver which industries are better or are more developed in 3D printing. Following the Wohlers Report 2017 [17] prediction for production applications (seeing Figure 18. 3DP use by sector. Wohlers Report 2017), aerospace and industrial/business machines companies are leading the way with an 18,2 % and 18,8 % of the total resulting in these industries together make up more than one third of the total usage of 3D printing in different sectors.

According to this data the prediction for the development of 3D printing within the aerospace industry is very high. As a result, the first case that will be analysed is the suitability of 3D printing within these industries. Whilst both the aeronautical industry and the aerospace industry can be considered separate in some countries, they can be analysed together. Some examples of companies Airbus, Boeing and General Electric that have both aerospace and aeronautical industries.

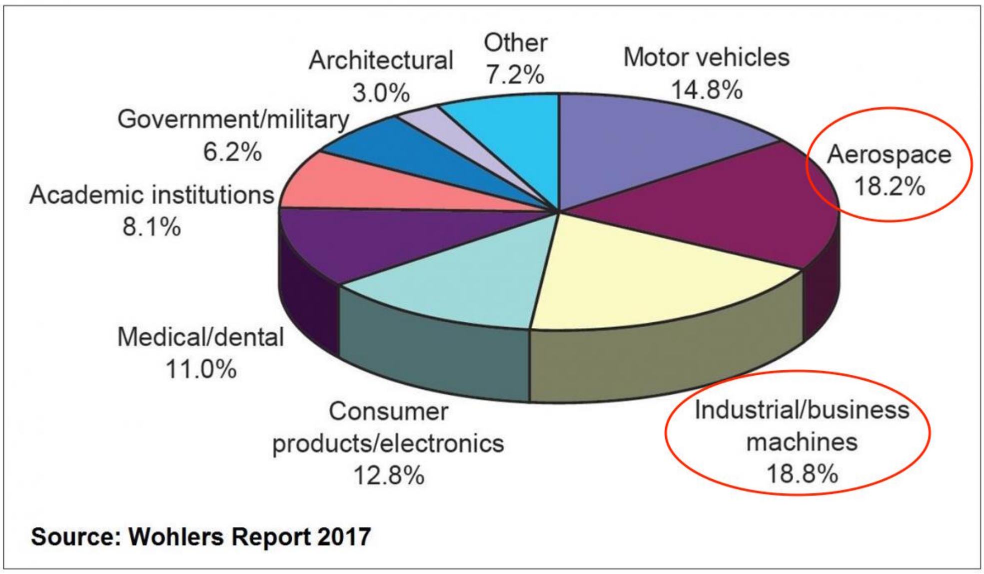


Figure 18. 3DP use by sector. Wohlers Report 2017

The downfall of this graph is that it is unable to accurately portray the future potential of this technology. *Ernst & Young* (EY) is a multinational professional service, which analyses different market researches and emerging technologies, particularly, AM. EY is able to outline which industry 3DP has a longer future in with more certainty.

According to the 2016 EY global 3D printing survey [15] (it is shown Figure 19) the future of 3DP will be in the Aerospace industry, Automotive and Mechanical and plant engineering industry. Instead the Automotive industry, according to Figure 18, will be the third industry to apply 3DP, this theory is also backed up by the data shown in Figure 19. Currently the Automotive industry has a medium application but in the future it is predicted to have high future potential. This industry is the same as the Medical and Dental industry and the Mechanical and plant engineering. The first currently has a medium application but it will have a high future potential and the Mechanical and Plant engineering, currently has a low application but in the future will have a high future potential according to the prediction of Figure 19. Therefore, the top four industries with the most future potential for 3D printing are the following, in order of precedence:

1. Aerospace and Defence
2. Automotive
3. Mechanical and Plant Engineering
4. Medical and Dental

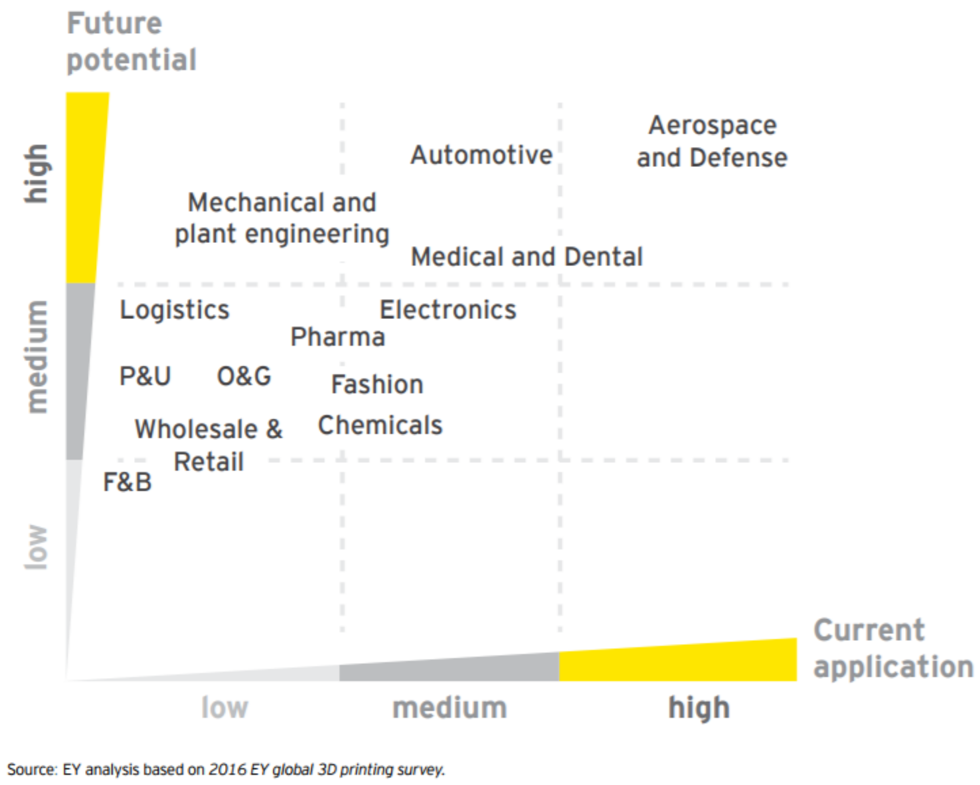


Figure 19. Current applications and future potential of 3D printing by industry

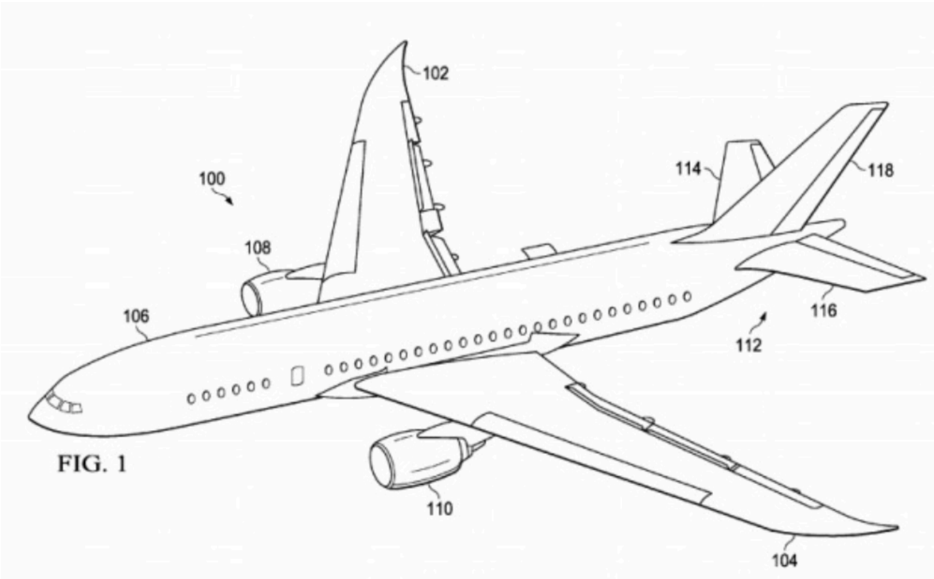
3.4. Evolution of 3D printing in the aeronautical field

The previous sections have shown that 3D printing is a good option for the aeronautical industry to invest in. This section will outline the evolution of 3D printing in the aeronautical field due to it being integral to the additive manufacturing industry.

In the late 1980s the first commercial rapid prototyping machine was developed at 3D Systems. The American aerospace manufacturer Pratt & Whitney was one of the first five enterprises to apply additive manufacturing [18]. Nowadays, Boeing has more than 300 different part numbers on 10 different aircraft [18] production programs, which amounts to more than 20.000 non-metallic additive manufactured parts that are on vehicles delivered to their customers. Approximately 150 parts in the forward fuselage area of the F/A-18 Super Hornet are produced through SLS [18]. Boeing has already different patents for its aircrafts, to use additive manufacturing. In the Figure 20 shows the parts that are patented to be made using 3D printing with the process of three-dimensional printing parts[5] [66]. This illustrative example, aircraft 100 has wing 102 and wing 104 attached to the body 106. The aircraft 100 include the engine 108

[5] Three-dimensional printing parts: it is a process of making a process of a making a solid object of virtually any shape from a part definition file. Three-dimensional printing is an additive process where successive layer of materials are laid down. Three dimensional printing may be performed with a variety of different materials such as polymers, plasters, metals and metal alloy. This process may allow for on demand manufacture of desired part

attached to wing 102 and engine 110 attached to wing 104. The body 106 has tail section 112. The horizontal stabilizer 114, horizontal stabilizer 116, and vertical stabilizer 118 are attached to tail section 112 of body 106 [66]. Nowadays, General Electric [4] is a company that is developing diverse parts of aircraft engines and is investing to use AM in its processes.



Schematics from Boeing patent application

Figure 20. Schematics from Boeing patent application with 3DP

Chapter 4

WHERE CAN AM BE APPLIED?

According to the previous section, the best industries to apply AM would be the Aerospace and Industrial/business Machines industries. However, it is fundamental to know which specific applications AM is suitable for. This chapter will carry out an analysis about different applications that are suitable for AM to be applied to.

The number of applications of AM has grown substantially over the years [19]. The typical applications [19] that AM is used for are for the following:

- Production of models and prototypes during a product's development phase
- Parts for pilot series production in medical, automotive and aerospace industry
- Short series production where tooling cost for casting or injection moulding would be too high
- Parts of high geometrical complexity which can not be produced by means of conventional manufacturing (moulding, grinding, milling, casting, etc.)

In order to study the applications with more precision, this study will refer to the study [20] of *Wohlers Associates,* carried out in 2017. This study predicts how organizations will use AM for a range of applications. Figure 21 is depicts a circular graph with the summary of the results of the study, presented in percentages. According to this graph, the application that is the most suitable to apply AM will be in the application of functional parts[6] with 33.8% of the total. The second most popular use of AM will be fit and assembly with a total of 16%. Finally, the third application will be education and research with a total of 10.7%.

When AM began, its first applications were typically only patterns for prototype tooling. According to the analysis however, [20] this application will no longer hold the majority of applications as a result of the uses of AM maturing and progressing over the years.

[6] Functional parts are those that relate to the function of the application

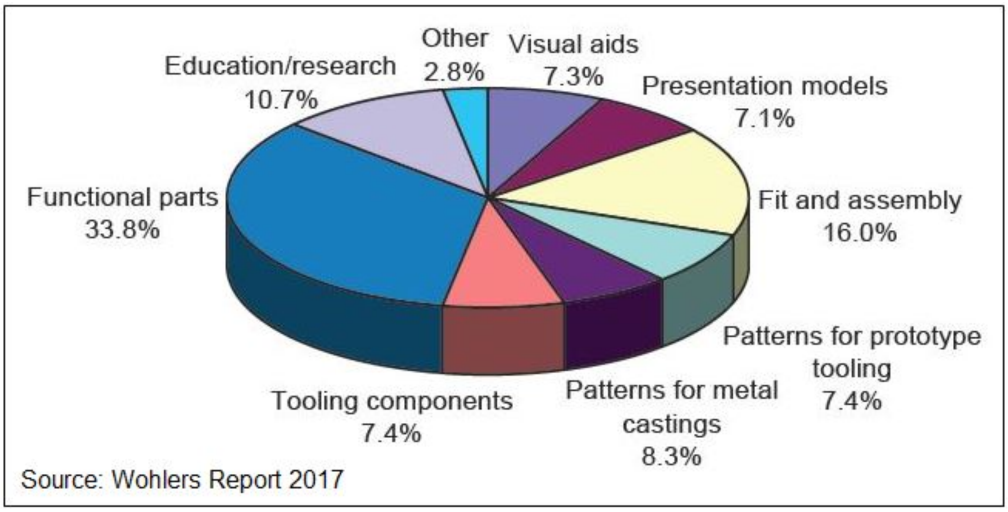


Figure 21. Applications of AM in 2017

This market analysis demonstrates that AM gained more importance over the years (Chapter 3.EVOLUTION OF THE ADDITIVE MANUFACTURING). Once the applications of AM have been analysed, it is basic to also study the global opportunities for AM across industries. *Deloitte* has carried out a study [21] of the different global opportunities in respect to diverse industries. The results of which are shown below in Figure 22.

Figure 22 organises the industries of the study into: consumer (AM is utilised in homes), small to mid-sized businesses and corporations. AM is utilised within the consumer industry for leisure activities, although in the near future it could also be implemented in food. The applications small businesses are entirely different to consumer use. The current use is in the manufacture of integral components for toys and auto parts. Investigations are also being made in this field for the application of AM with organ replacement in the human body. The creation of an organ with 3D printing would eliminate the need for a typical transplant according to *The Guardian* [22]. Organovo [23] is an example of company that is investing in the research of organ creation. In December 2010, Organovo created the first blood vessel to be printed using cells cultured from a single person. Currently, this company among others are researching into creating a heart with AM.

Finally, the corporation industries are utilising AM for industry R&D (for prototyping) and also for aircraft and defence R&D. The research within of corporations is typically for consumer electronics (dvd players, flatscreen TVs, cell phones among other) and furniture. As a result of this analysis, global opportunities of the corporation industries are mainly the production of functional parts in which Aircraft and defence is invested more than $ 9B [19]. Regarding this affirmation, the manufacturing process of functional parts created for use in the aeronautical industry is suitable for AM to be invested in.

		Target user		
		Consumer	Small to mid-sized business	Corporations
Printer readiness	In need of further R&D		• Organ Replacement, $30B	• Furniture, $20B • Consumer electronics, $289B
	Nearing commercial use	• US Prepared food, $23B	• Bicycles, $6B • Guns and ammo, $11B • Global apparel, $1T	• Life sciences R&D, $148B • Home building and improvement, $678B • Power tools, $22B
	In use	• Craft and hobby, $30B • Animation and gaming, $122B	• Medical prosthetics, $17.5B • Retail hardware, $22B • US Auto parts stores, $40B • Toys, $80B	• Industrial R&D (for Prototyping), $23B • Aircraft and defense R&D, $9B

Figure 22. Global opportunities for AM across industries

4.1. Commercial aerospace and defence applications

This section will analyse the potential applications inside of the aeronautical field. *Deloitte* has carried out research [21] about the current and potential applications of AM within commercial aerospace and defence and space. These conclusions have been summarised in Figure 23, listing the different applications, current and potential. According to this study, the current applications of the commercial aerospace are printing replacements parts, printing low-volume complex aerospace parts and concepts modelling and prototyping. The potential applications in this field are the repairing of parts.

	Current applications	Potential applications
Commercial aerospace and defense	• Concept modeling and prototyping • Printing low-volume complex aerospace parts • Printing replacements parts	• Embedding additively manufactured electronics directly on parts • Printing aircraft wings • Printing complex engine parts • Printing repair parts on the battlefield
Space	• Printing specialized parts for space exploration • Printing structures using lightweight, high-strength materials • Printing parts with minimal waste	• Printing on-demand parts/spares in space • Printing large structures directly in space, thus circumventing launch vehicles' size limitations

Figure 23. AM applications in the Aerospace and Defence industry

Chapter 5

CASE STUDY: SEATBELT

As aforementioned the additive manufacturing shall be a technology that will be able to be used in the aeronautical field. According to this prediction a case study has been drawn up. This case study will be an aircraft seatbelt in which the traditional method, the additive manufacturing method of manufacturing will be analysed alongside its economic impact in the business world.

5.1. Introduction to aircraft seatbelt

According to the definition of a seatbelt [24], it is a vehicle safety device designed to secure the occupant of a vehicle against harmful movement that may result during a collision or a sudden stop. Usually when one thinks of a seatbelt one normally considers car seatbelts, however in this case this study will examine aircraft seatbelts.

The primary goal of seatbelt [24] is to save lives in the event of a car crashing, turbulence or collisions on the runway (in the case of aircraft seatbelts).

One difference between car and aircraft seatbelts is the seatbelt position. The car seatbelt position is a shoulder belt because car accidents typically involve forward, backward or sideways motion. Due to this, the seatbelt is designed to stop the entire upper body from bouncing around from sudden acceleration or deceleration. On the other hand, the aircraft seatbelt´s function is to protect a passenger from upwards and downwards movement such as with turbulence. However, the seatbelts of the pilot and crew have shoulder belts to compensate for their position in the aircraft.

Each airline chooses the seatbelt models that are most convenient for their aircraft and the manufacturer of seatbelts customizes this design. It is important to fulfil all certifications of EASA [25] (European Aviation Safety Agency) and FAA [26]. There are many different models of domestic aircraft seatbelts (passenger only). The four most common airline seat belts can be seen below (
Figure 24):

Figure 24. Models Airline Seatbelts

Figure 24 shows some variations according to different models of the seatbelts [27]. Theses variations are the shapes of buckles and the the shape of the clasp. In order to analyse the diverse models of seatbelts in Table 2 is shown the principal properties of these. The properties of the models that show in Table 2 are according to the FAA [26] Technical Standard Order7 (TSO) C22g.

[7] TSO is a minimum performance standard for specified materials, parts, and appliances used on civil aircraft.

SPECIFICATIONS	MODELS A	B	C	D
Overall Extender length	63.5 cm (25”)	63.5 cm (25”)	63.5 cm (25”)	63.5 cm (25”)
Extender Weight without weight belt	179 g (6.3 oz)	183 g (6.4 oz)	264 g (9.3 oz)	179 g (6.3 oz)
Buckle Colour	Brushed aluminium	Black plastic latch lift, Chrome steel frame	Brushed aluminium latch lift, chrome steel frame	Brushed aluminium
Buckle Material	Aluminum frame; steel internal components	Steel frame; steel internal components	Steel frame; steel internal components	Aluminum frame; steel internal components
Clasp Colour	Chrome	Chrome	Chrome	Chrome
Clasp Material	Steel	Steel	Steel	Steel
Belt Width	5.1 cm (2”)	5.1 cm (2”)	5.1 cm (2”)	5.1 cm (2”)
Belt Material	Woven nylon webbing	Woven nylon webbing	Woven nylon webbing	Woven nylon webbing
Belts Colour	Satin black	Satin black	Satin black	Satin black
Proof Strength	13344.66 N (3000 lb)	13344.66 N (3000 lb)	13344.66 N (3000 lb)	13344.66 N (3000 lb)

Table 2. Properties of models seatbelts

- **The model A** (Figure 25) is the seatbelt most commonly used by the major domestic and international airlines such as ATA, Continental, Delta, JetBlue, NWA, TWA, Vueling, Norwegian, Qatar and many other airlines [27]. According to the properties of model A show at Table 2 is the model the lowest weight, its weight is 179 g (buckle plus clasp), the total weight is 300 g as a result, the weight of the belt is 121 g. Another difference respect to other models is the buckle materials; this is made up aluminium for the frame part and steel for the internal components. The belt is made up woven nylon webbing.

Figure 25. Model A of Seatbelt

- **The model B** (Figure 26) is the seatbelt that is primarily for use on Southwestern airline and Turkish airlines, which are airlines that use Boeing 737 aircraft [27]. This model is also used on some private business aircrafts. The material that is used to the buckle is steel for frame and internal components. The colour of buckle is different respect to other models in this case is made up black plastic latch lift and chrome steel for frame. These properties are shown in the Table 2.

Figure 26. Model B of Seatbelt

- **The model C** (Figure 27) is a seatbelt that is used by Alaska airlines, some older airlines (particularly charter jet aircraft), private business jets, smaller commuter aircraft and private aircraft [27]. It has heaviest weight of all the different models of seatbelts with 264 g (shows in the Table 2). The belt material is different to other models; this is made up woven nylon webbing. The length of model B is similar of other models, that is 63.5 cm.

Figure 27. Model C of Seatbelt

- **The model D** (Figure 28) is a seatbelt that is used in Cessna and Gulfstream jets, business jets, some older airlines, smaller commuter aircraft, private planes and helicopters [27]. The overall extender length is 63.5 cm and the extender weight is 179 g (shows in the Table 2).

Figure 28. Model D of Seatbelt

In order to choose the model best suited to this study, it is crucial to consider one which will have a clear economic impact within the industry and an airline allowing for an analysis to be made. With this in mind, Model A (Figure 25) has been chosen as; it is used by the vast majority of commercial airlines [27]. Model A will be assessed for its suitability for additive manufacturing.

5.2. Traditional manufacturing of Model A

This section will examine the different properties of the model A such as the dimensions of all its parts, the certifications that the manufacturer is required to have and the tests that the seatbelts need to pass. The lifespan of the seatbelts that are used in traditional manufacturing will also be analysed.

The size of the different parts of model A [28] are shown in Table 3 below and the dimensions can be found in Figure 29. These sizes are according to the ETSO C22g that is the European Technical Standard Order [25]. The biggest part is part A that measures 9.3 cm and smallest is D with 0.71 cm.

Figure 29. Model A Dimensions

Model A dimensions (cm)

A	B	C	D	E	F
9.3	5.91	2.77	0.71	2.03	1.09
G	**H**	**I**	**J**	**K**	
4.93	4.85	6.1	6.5	1.98	

Table 3. Model A Dimensions

As aforementioned each airline chooses the seatbelt models that are most convenient for their aircraft and a large majority of airlines choose the model A. For this the safety functions of each model are also taken into consideration. These functions are regulated by EASA [25] and FAA. In order for manufacturers to be permitted to produce seatbelts, these governing bodies must certify them.

Some certifications are ETSO-C22g (safety belts), EASA Amendment 11- CS25.561 (emergency landing conditions), EASA Amendment 11-CS25.785 (Design and Construction seat belts, safety and hardness), EASA Amendment 11-CS25.562

(Emerging landing conditions for new models of aircraft such as A330, A380 and B777), EASA C21, EASA E.2. C11 and aerospace standard (SAE) AS8049 among others. According to EASA SIB (Safety Information Bulletin) No 2010-15R1 the seatbelt manufacturers that the EASA certify to make aircraft seatbelts are AmSafe, Anjou Aeronautique, Autoflug, Davis Aircraft Products Co., Schroth Safety Products GmbH and Pacific Scientific [25,29,30,31,32].

In order to analyse seatbelts for additive manufacturing it is necessary to know what are the causes of degradation of the seatbelts made with traditional manufacturing. According to a *research project of EASA 2010/5* (which outlines the process to certification of seatbelts)*, called SEBEB-Seat belt degradation [25]*, that during the lifetime of a seatbelt it is considered that mechanical performance may deteriorate in response to normal use and exposure to environmental conditions such as natural aging of the fabric and in-service contamination by various liquids and substances. Additionally, some seatbelts may be exposed to improper cleaning and poor maintenance. The research was made up of two phases. The first phase was to certificate the numbers of years that the seatbelts can be in service; dynamic testing checked this. The second phase was commissioned in order to improve upon the data obtained in phase 1 however with a static test. As a result, the following recommendations/results were obtained for seatbelt manufacturers:

- It is recommended that inspection of the seatbelts should be carried out a maximum interval of every 12 months [25], or more frequently depending on the extent of use. This recommendation will do by the airline.

- It would be prudent to adopt a maximum lifespan for belts in service of 10 years [25] from the date of manufacture (this would include both time in storage and service life) until further information can be gained about long-term performance. This lifetime is based on the natural deterioration of polymer fibres that occurs even when they are in storage in ideal conditions.

- It is recommended that guidance be issued to air operators about the importance of ensuring that belts are made up of matched parts. In the research when gathering belts from various sources, it was common to find belts, which were assembled from mismatched parts [25].

- The 30% of the total number of belts to be tested required to have been repaired [25 29 30 31].

- According to the test results the yield strength in the seatbelts of model A was 3000 lbs (the same value that was shown in the Table 2 [27,25,32].

This research [25] shows the rated load (3,000 ibs) that the seatbelts and the materials should have that are usually utilised in order to be certified with traditional manufacturing. From this research this thesis will examine which is the best material to replace the traditional manufacturing of the seatbelts by using additive manufacturing.

5.3. Additive Manufacturing of Model A

The goal of the section is to identify a material that will reduce the weight of aircraft and obtain the same benefits or better than traditional manufacturing (TM). In other words, the performance of the materials used will be improved, in order to reduce fuel consumption. As a result, the material must have a high strength, low density and the material must be compatible with other materials to make up a new alloy. It must have the same certifications of FAA and EASA [33,34,35] such as TM. This section will make a comprehensive comparison of diverse materials and will choose the most suitable material to be made with AM.

5.3.1. Additive manufacturing of the buckle and the clasp

The buckle and clasp of Model A will be analysed with different materials which are used in additive manufacturing that could be able to reduce the weight of the components without losing the same benefits or mechanical properties that are achieved by using TM. Currently, the parts of the buckle are currently made using aluminium for the frame and the clasp. Steel is used to construct the internal components such as the spring.

According to different research about the aerospace industry there are many options for materials that can be implemented in AM. Some examples of metallic materials utilised with the electron beam additive manufacturing, that is the printer that is utilised by some companies such as GE [4], are cobalt alloys, steel, nickel alloys and titanium alloys. Table 4 shows the main mechanical properties [34,36,37,38] of the different typical alloys of these materials. In the case of cobalt base alloys CoCr28Mo is analysed below, alongside this are steel 1020, Inconel 718 (nickel alloy) and finally Ti6Al4V, a titanium alloy [4]. These alloys have been selected as they are the most suitable for the use of additive manufacturing in the aeronautical field as determined by GE in a study [4].

Steel is the material that is currently being used for the internal parts of Model A, the objective of this study is to find a new material that improves this current material and to reduce the overall weight. This material will therefore not be considered in this process for these reasons. However in the case that the materials that have been considered are not suitable to weight reduction or improvements, then steel this will be utilised as it is a suitable alternative.

Cobalt is useful for applications [4,38,40] that utilize its magnetic properties, corrosion resistance and its strength at elevated temperatures. The cobalt base alloys materials are alloyed with chrome, nickel, and tungsten. Due to the high cost of these alloys, these are used where severe conditions prevail and where high temperature, strength and hardness are required. The most popular cobalt material that is being utilised in AM is the CoCr28Mo. This alloy is typically utilised in engine parts from jet engines to industrial gas turbines and the biomedical industry. Regarding Table 4, cobalt has a high density. The goal of this case is the reduction of weight and to improve the actual properties of the seatbelts. Because of this, these alloys will not be the best material to use for seatbelts.

Nickel can be applied in its elemental form or alloyed with other metals and materials. Various applications of nickel have made significant contributions to the supply materials in different industries. This is because Nickel is a versatile element and will alloy with most metals as well as having a high corrosion resistance and heat resistance. This is the reason why it is applied in aircraft gas turbines, chemical and petrochemical industries and steam turbine power plants, amongst other applications. The most popular nickel alloy for additive manufacturing [4], specifically for EBM, is Inconel 718. It is a metal that is also highly resistant to the corrosive effect of hydrochloric acid and sulphuric acid. According to Table 4 nickel demonstrates excellent tensile strength and excellent young's modulus, even better than titanium. However, due to the high density of nickel this material will be not considered in this process.

	Cobalt	**Steel**	**Nickel**	**Titanium**
Density [g/cm3]	8.90	7.8	8.91	4.51
Young's Modulus [GPa]	209	215.5	200	105
Yield stress [MPa]	650	250	550	880
UTS [MPa]	1160	420	965	1400

Table 4. Mechanical Properties of cobalt, steel, nickel and titanium

However, there is also a trend in the industry indicating titanium will be the most popular material for this process [4]. This is due to the properties of titanium, it is a transition metal with a silver colour that has low density and high strength. Titanium (Ti) is also resistant to corrosion in seawater, aqua regia and chlorine. This is the reason for its increasing usage within the aerospace industry. The different mechanical and physical properties of aluminium (Al), Ti and Steel are displayed below in Table 5:

	Al (2024)	**Ti**	**Steel (1020)**
Density [g/cm3]	2.7	4.51	7.8
Young's Modulus [GPa]	72.2	105.2	215.5
Yield stress [MPa]	276	880	250
UTS [MPa]	700	1400	420
Elongation at break (in 50 mm) [%]	40	25	25
Poisson's Ratio	0.33	0.34	0.30
Electrochemical Potential [V]	-1.7	-1.6	-0.4
Resistance to Corrosion	Good	Excellent	Not bad

	Al (2024)	Ti	Steel (1020)
Melting temperature [ºC]	660	1667	1536
Dilation Coefficient [X10^-6/K]	22.5	8.8	12.1
Rivet weight [g]	0.85	1.41	2.45

Table 5. Mechanical Properties of Al, Ti and Steel

Aluminium and steel are analysed in respect to titanium because they are the material utilised in the buckle of seatbelt shown in Model A. Each seatbelt manufacturer has its own unique combination of aluminium and steel; this ratio is not available as published information. This thesis will assess the diverse properties of the materials Aluminium 2024 and steel 1020, which are currently utilised.

According to Table 5 the titanium density (4.51 g/cm^3) is the lowest of the three materials. This is a crucial property to reduce the weight of the seatbelts. The second property displayed in Table 5 is young's modulus[8], it is important to have a high value as the material will be more elastic and the will be able to support more the impact during the dynamic test (regarding to certification of seatbelts with the process of TM). Steel has the highest value with 215.5 GPa but Model A only has its internal components and clasp made with steel, as the majority is made of aluminium. Due to the majority being manufactured with aluminium, titanium would make for a better material to implement in seatbelts as it has a higher value. However, a mix of steel and titanium parts is not possible or practical when considering AM, only an alloy would be suitable. Another crucial property to study is the tensile stress[9] (UTS), whereas, steel tests well for UTS it is only used for internal components, therefore titanium would be suitable due to its much higher value and resistance. When a material is taken into account for the aeronautical industry its resistance to corrosion is crucial because these materials are exposed to diverse situations. In the case of the titanium, it has a better resistance to corrosion that other materials, again indicating its suitability. Finally, the melting temperature is another necessary property when wanting to implement a material. In the case of a fire resistance is needed in these conditions. Out of the three materials titanium has the highest melting point temperature with 1667ºC. All together, this is strong evidence for titanium being a suitable candidate as the best material to implement with additive manufacturing or other manufacturing processes due to its low cost and low impact to processes.

The company General Electric (GE)[4,41] is currently using titanium alloy to build a functioning miniature 3D-printed jet engine with titanium components. The titanium that is considered for additive manufacturing is an alloy that is made up for titanium, aluminium and vanadium (Ti-6Al-4V). It is an alpha-beta titanium alloy featuring high strength, low weight ratio and excellent corrosion resistance. This is one of the most commonly used titanium alloys and is applied in a wide range of applications where

[8]Young's modulus measures the mechanical property of linear elastic solid materials..

[9] UTS is the resistance of a material to breaking under tension

low density and excellent corrosion resistance are necessary. Moreover, in addition to being used for the aerospace industry it is also used for biomechanical applications such as implants and prostheses. This alloy is fully heat treatable in section sized up to 15 mm and can be used up to approximately 400ºC.

There are two alloys with the same structure [36], these are Ti6Al4V Eli (grade 23) and Ti6Al4V (grade 5). The essential difference between the two is the reduction of oxygen content to 0.13% (maximum) in grade 23. This results in improved ductility and fracture toughness, with some reduction in strength. Grade 23 has been widely used in fracture critical airframe structures and for offshore tubular components used in offshore wind farms. The mechanical properties for the application of fracture critical airframes can be enhanced through being processed and treated with grade 23 alloys. The most commonly utilised method in EBM for titanium alloys is constructing with metals in a powder form. According to *the company Arcam[36],* the grade 23 alloys have been improved by the company's alterations. This is shown in Table 6 and Table 7 below.

Chemical Specification (%)

	Arcam Ti6Al4V ELI[10]	**Ti6Al4V ELI Required[11]**
Al	6	5.5-6.5
V	4	3.5-4.5
C	0.03	<0.08
Fe	0.1	<0.25
O	0.10	<0.13
N	0.01	<0.05
H	<0.003	<0.012
Ti	Balance	Balance

Table 6. Chemical Specification of Ti6Al4V

[10] Typical

[11] ASTM F136: Standard Specifications for wrought Titanium 6 Aluminium 4 Vanadium ELI (Extra low interstitial)

Mechanical Properties

	Arcam Ti6Al4V ELI[12]	Ti6Al4V ELI Required[13]
Yield Strength (Rp 0.2)	930 MPa	795 MPa
UTS	970 MPa	860 MPa
Rockwell Hardness	32 HRC	30-35 HRC
Elongation	16%	>10%
Reduction of Area	50%	>25%
Fatigue Strength @600 MPa	>10.000.000 cycles	>1.000.000 cycles
Young's Modulus	120 GPa	114 GPa

Table 7. Mechanical Properties of Ti6Al4V ELI

Table 6 shows an improvement to the standard specification for Ti6Al4V achieved by Arcam [36]. According to Table 7 with Arcam´s [36] Ti6Al4V ELI yield strength has been improved from 795 to 930 MPa and it has also been improved in respect to Ti, which has a value of 880 MPa (see Table 5). The Young's Modulus is another measurable mechanical property that is also made superior to ASTM F136, as the Arcam Ti6Al4V has a value of 120 GPa and in respect to Ti, this is an improvement as well. The reason for the inclusion of this data from Arcam is to demonstrate another clear benefit of manufacturing using additive manufacturing, as it allows for materials to be drastically altered according to the function required.

The reason for using titanium is to reduce the weight of components such as brackets, which are important support structures. Figure 30 shows an example of how weight and volume can be reduced when additive manufacturing and titanium is applied [64].

Indeed, although it uses less material, this design still maintains the required stiffness. According to the company *Materialise*, the total volume of the piece would be reduced by 63% with the use of titanium [64].

Regarding this investigation into seatbelt manufacturing, if the same process was applied to model A, it would decrease in volume by around 63%, then its weight would also decrease by around 63% [64]. According to Table 2 the weight of model A is currently 179 g however, with the use of titanium the weight would be reduced to 66.23 g.

[12] Typical

[13] ASTM F136: Standard Specifications for wrought Titanium 6 Aluminium 4 Vanadium ELI (Extra low interstitial)

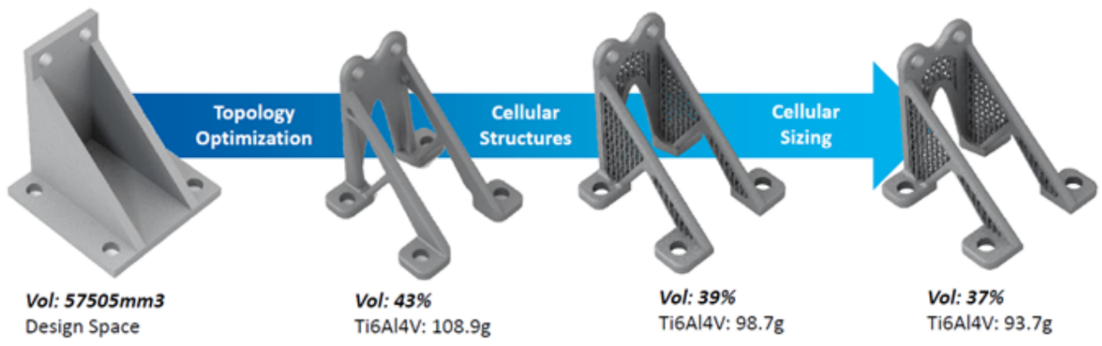


Figure 30. Optimization of a piece with titanium and AM

As a result, the material chosen will be the Ti6Al4V (shown in Figure 31) powder and the AM printer that will be used will be EBM because it the best option to use with AM, improving the properties of TM and reducing the weight.

Figure 31. Buckle and Clasp of Model A with AM

5.3.2. Additive Manufacturing of the belt

The belt is an important part of the seatbelt that is required to pass different safety assurance controls. It is also necessary that it is constructed with extremely resistant materials. Currently the material that is utilised is woven nylon webbing, a polymer that is made with TM. Because the belt is an integral part of the seatbelt, it is imperative to investigate the application of 3D printing and the materials, which would be suitable for the process. As previously explored in Chapter 1 (see section 1.3.1), there are many plastic materials that can be used with 3D printing. However, the company *ECK Plastic Arts* presents a selection of polymers/plastic materials [42] that are usually utilised for additive manufacturing and provides the data of the mechanical properties of these materials. These materials will be outlined below in terms of their suitability.

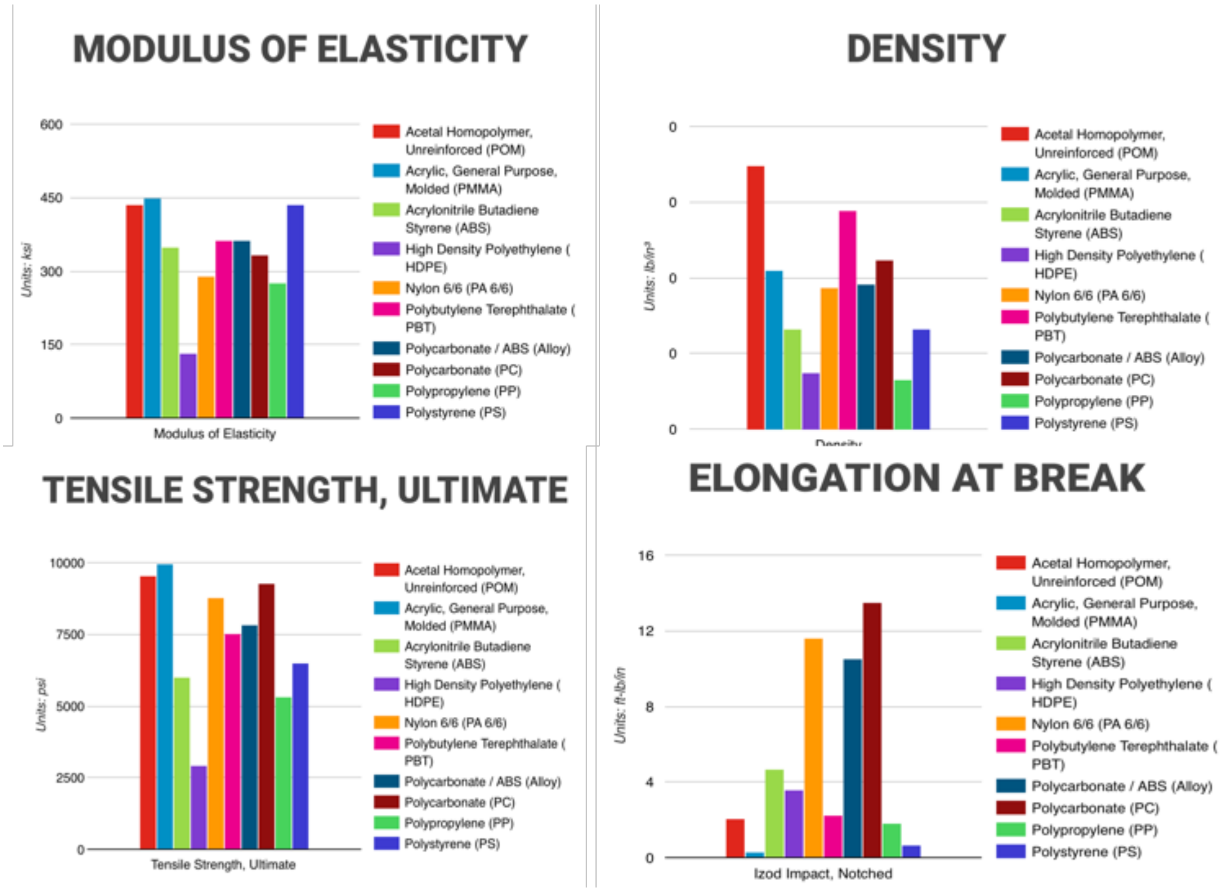


Figure 32. Material Selection Guide by ECK

Figure 32 summarises diverse crucial mechanical properties of materials [42] in order to choose the best material for the manufacturing of the belt. The first property to analyse is the density, in the interest of decreasing the total weight of the seatbelt. The low-density materials are polypropylene (PP), high-density polyethylene (HDPE), polypropylene (PP), acrylonitrile butadiene styrene (ABS), polystyrene (PS) and nylon 6/6 (PA 6/6). In respect to these materials, the range of density is from 0.94 g/cm3 to 1.41 g/cm3 as a result; the difference between them is minute, so all of the materials that are shown in the graphs are valid for consideration. As with the metal alloys, the Modulus of Elasticity or Young´s modulus is the second property that must be examined. Regarding Figure 32, the best materials with higher values in this property are Acrylic General Purpose Molded (PMMA), Acetal Homopolymer Unreinforced (POM), PS and Polycarbonate/ABS (alloy). However, the materials with better values in UTS are PMMA, POM, polycarbonate (PC) and PA 6/6. Finally, the last property for this first analysis is elongation until breakage; the best materials in terms of this value are PC, PA 6/6 and polycarbonate/abs (alloy). As a result of these conflicting results, it is difficult to deliver the best material for the belt component from simply this first analysis. As a consequence, another analysis will be conducted that will examine thermoplastics that are most utilised for additive manufacturing [43]. These are ABS, Polylactic acid (PLA), Polyethylene Terephthalate (PET) and PA 6/6. Their mechanical properties [44,45,46,47,48] are presented in Table 8.

PLA is polylactide, or polylactic acid, is a thermoplastic, which is comprised of filaments. It is also one of the most popular thermoplastic materials within 3D printing, according to research by GE [4]. Since PLA is made from corn-starch or sugar cane it is biodegradable as a result. This polymer[14] is used in diverse applications, including rapid prototyping, candy wrappers and biodegradable sutures. According to Table 8, it has a low density, but not the best and the value of its yield stress is the second best. Therefore, this material is not the most suitable to use in the belt.

PET is polyethylene terephthalate is the most common thermoplastic polymer resin made from polyester and is used in fibres for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fibres for engineering resins. Despite the material´s durability, it has the worst value of density (see Table 8) and will therefore, not be not selected for the belt material.

ABS is acrylonitrile butadinene styrene; it is a strong, durable material with excellent dimensional accuracy [4]. To implement ABS in AM, the filament must be heated to a relatively high 230-250 ºC. The higher melting point of ABS makes for objects that are relatively warp and crack-resistant. ABS is used in rapid tooling and for creating concept models. Out of the four materials selected (Table 8) ABS has the worst value of UTS, as a result this material is also not suitable to use in the belt.

PA 6/6 [49] is a type of polyamide or nylon[15]. There are many types of nylon such as nylon 6/6 (PA 6/6), nylon 6, nylon 46, nylon 510 and nylon 1.6. However, the nylon that is most commercialized for engineering applications and textiles is PA 6/6. PA is often used for components in gears, gearboxes and plastic bearings because of its inherent low-friction properties. Nylon is used for 3D printed models for high heat applications when ABS is not an option [49]. According to Table 8 PA has the lowest density of all the options and has the best properties of the four materials. As a result of this, the material that will finally be utilised to produce the belt will be Nylon 6/6, because it is the most suitable material for this application, more so than other materials.

Although the material is the same that is as of yet being utilised for traditional manufacturing, the application of additive manufacturing to the process will reduce the total weight by 30% [13]. Currently the weight of the belt is 121 g with TM however, with AM it would be only 84.7 g. Moreover, according to *cimquest [50],* the process of AM would allow the volume of the belt to be reduced drastically without losing or

[14] Polymer is a large molecule or macromolecule composed of many repeated subunits. This allows for more flexibility in its uses in production. Polymers range from familiar synthetic plastic such as polystyrene.

[15] Nylon [52,53] is a generic designation for a family of synthetic polymers, based on aliphatic or semi-aromatic polyamides. Nylon is a thermoplastic silky material that can be multi-produced into fibers, films or shapes.

compromising on mechanical properties such as high tensile strength and durability. The printer that would be utilised to make the belt will be EBM, because the nylon will be applied in its powder form. Usually the method most applied to nylon is FDM printing, but there are some companies such as *prodways technologies [51]* that print with PA 6/6 (see Figure 33) in its powder form as well as using the EBM method for this material. Moreover, there is an additional benefit to proposing the same printing method as would be used with the production of the metal parts. This is because removing the necessity for having two different printing methods would reduce the total cost and lead-time

	PA 6/6	**PLA**	**PET**	**ABS**
Density [g/cm3]	1.14	1.25	1.38	1.2
Young's Modulus [GPa]	1.6-23	3.5	2-2.7	2
Yield stress [MPa]	80	60	-	42
UTS [MPa]	60	50	55	40

Table 8. Mechanical Properties Nylon 6/6, PLA, PS and ABS

Figure 33. Model A with AM

5.4. Economic impact of Ti6Al4V and PA 6/6

This section will carry out a projection of the impact that the application of AM with Ti6Al4V and PA 6/6 (see Figure 33) would have in an airline. The airline that has been chosen is Vueling. It is a Spanish low-cost airline based at Prat de Llobregat, Barcelona. It is the largest airline in Spain by fleet size and the number of destinations that it provides in its service. Vueling serves over 100 destinations (see Figure 34) in Africa, Asia and the Middle East. In 2016, the airline carried more than 27 million passengers, with a load factor of 81%; [54] this is a measurement of how full an aircraft is for a flight. Moreover, in 2017 Vueling yielded profits of $ 220.80 M, 2.13.3% more than 2016´s profits. The company obtained revenue of $ 2.49 B that was 2.9% higher than 2016 [55]. These are compelling reasons to consider Vueling as the airline for the analysis

Figure 34. Vueling Destination

The goal of this projection is to demonstrate the impact of additive manufacturing in an airline through two different study scenarios. The impact of altering the manufacturing methods will be calculated by an analysis of weight reduction and project cost reduction of the Vueling fleet combined with an estimation of fuel reduction/save each year according to the number of operations in 2017. The analysis will follow with the display of the annual fuel save and the annual pollution reduction of CO_2 (see Figure 35).

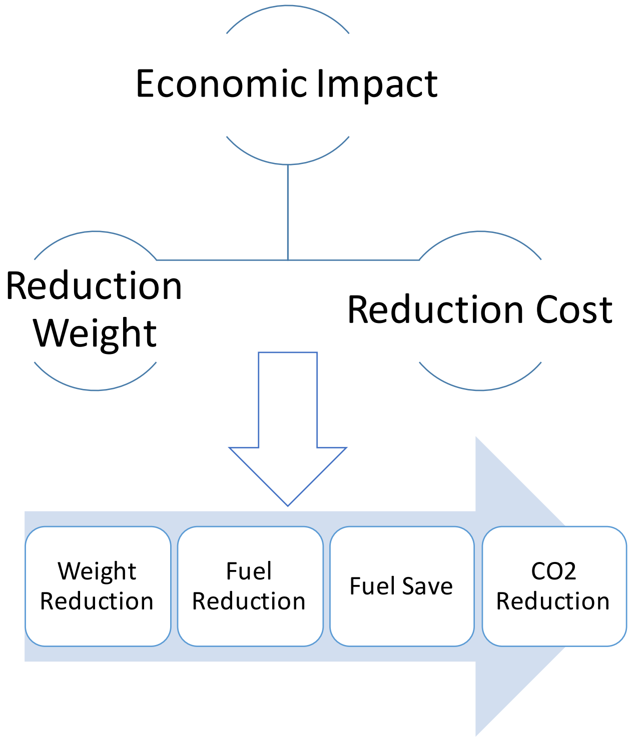


Figure 35. Objectives of the economic impact

Currently Vueling has 114 aircraft in its aircraft fleet with three different models of airbus. The Vueling fleet is made up of 75 aircraft of A320, 19 aircraft of A320 space flex, 5 aircraft of A319 and 15 aircraft of A321 [54] (shown in Table 9). According to different sources from Vueling in 2017, this company has around 18 000 flights every month on average when including every stop an aircraft makes. In the summer of 2017 Vueling had around 22 000 flights every month and 14 000 flights every month in the winter. As a result, the total number of flights in 2017 was approximately 216 000 flights.

Aircraft	At Service	Passengers	% of use	Number total of Flight in 2017	Number total of passenger in 2017
A320-200	75	180	65.8	142,128	25,583,040
A320-200 space flex	19	186	16.7	36,072	6,709,392
A319-100	5	144	4.4	9,504	1,368,576
A321-200	15	200	13.1	28,296	5,659,200
	Total	20,754	**Total**	216,000	39,320,208

Table 9. Vueling Fleet

In addition, *The rise of 3D-printing: the advantages of additive manufacturing over traditional manufacturing,* indicates findings that show that a reduction in one kilogram to an aircraft´s weight equates to a saving of $1,300 in fuel per year [1] and avoids the expulsion of 383.33 kg of CO2 [56]. Regarding to the Vueling Fleet, this chapter shall assess how much fuel would be saved and as a result, how much CO2 would be reduced. This analysis is broken down into two parts (shown in Figure 36); the first part will make a projection of the scenario where all of the fleet of Vueling will have additive manufacturing applied to the aircrafts. The second part will assess the impact of a more realistic situation where only a minimal amount of aircraft seatbelts, such as 30%, will be affected by additive manufacturing. This is taking in mind, that the application of additive manufacturing would be implemented in increments, as an airline would most likely not substitute a product that is not yet faulty.

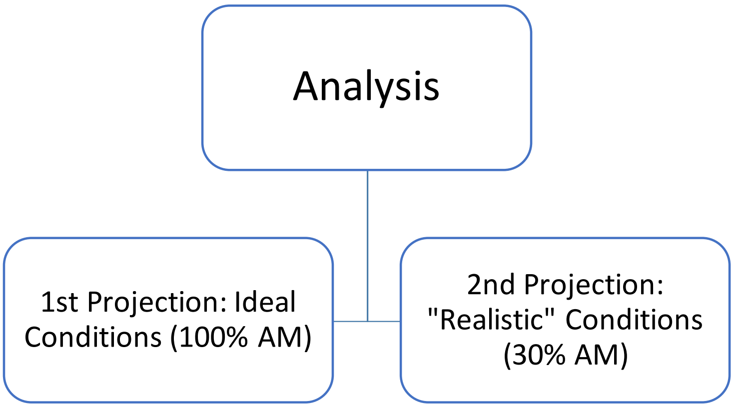


Figure 36. Parts of the analysis

5.4.1. First projection of the analysis: ideal conditions

If the conditions of the first projection are met, the total weight reduction to the fleet that will be obtained can be predicted by multiplying each model of aircraft by its maximum capacity of passengers (data of Table 9). The numbers of total seatbelts in the entire fleet are 20,754 however; this reduction will only be valid in the case that all aircraft in the fleet are in active service.

When the changes in manufacturing (TM to AM) are applied to the total weight of the seatbelts, the weight will be reduced by 50.31 % (see previous sections 5.3.1 and 5.3.2). Currently, the total numbers of seatbelts, 20,754, are made with TM. Therefore, the total weight (each seatbelt 300g) is 6,226.2 kg with TM. But, if AM manufacturing is applied to the entire fleet, this weight will be reduced incredibly to the total weight of 3,132.40 kg (see in Figure 37). The sum reduction of the total kg is by 50.31 %, resulting in a difference of 3,093.8 kg between the two manufacturing processes.

In order to analyse the amount of fuel saved annually, the number of passengers and the total usage of different aircraft models within the fleet are needed to calculate the total passengers during a full year. From this calculation, the total weight can be approximated, allowing for a total of fuel consumption and CO2 emissions to also be

calculated. It should also be taken into account that the total passenger count should be regarded as an approximation only, as different aircraft have different rates of usage (see
Table 9)

In order to obtain the total weight that will be reduced by a change in the supply chain, the flight data from the previous year, 2017, will be used for this study. The total flights of 2017 have been multiplied by total passengers to achieve this figure (as each passenger equates to one seatbelt). The result of this calculation is 39,320,208 passengers/seatbelts, if this total is constructed using TM, the total weight will be 11,796.0624 tons, on the other hand, AM will only result in a total of 5,934.6 tons. As a result, the total weight reduction will be 5,861.46 tons. According to the research of *The rise of 3D-printing [1],* Vueling will save $7,619,898 in fuel per year (the total weight reduced 5,861.46 when multiplied by an average cost of $1,300 fuel /year). The tons of CO2 that will not be expelled will be 1,185.95 Tons of CO2 [56] (the total weight reduced, in kg, has been multiplied by 383.33 kg of CO2) (shown in Figure 37).

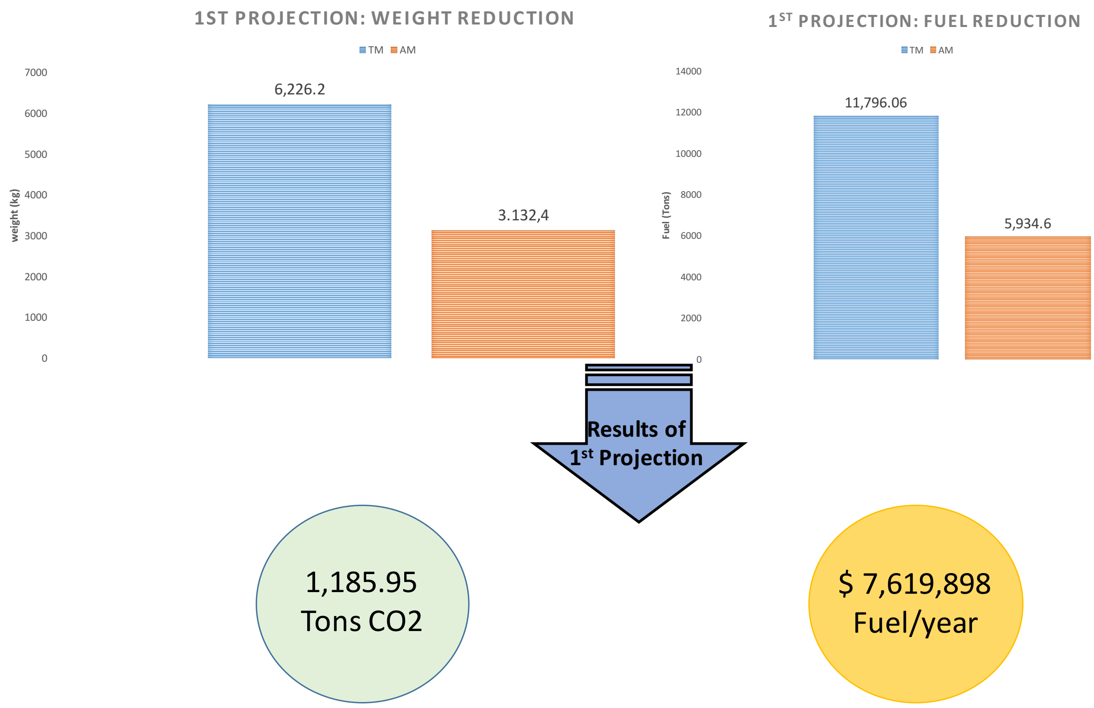


Figure 37. Summary of The 1st projection

5.4.2. Second Projection: realistic conditions

In the second and most realistic projection, all new seatbelts will be not implemented in all the Vueling fleet instantaneously. According to EASA 2010/5 [31] each 12 months the airlines are required to carry out an inspection of seatbelts and to replace each seatbelt after a lifespan of 7 years with a new model. If only approximately 30 % of seatbelts are required to be replaced at once, then AM would not be implemented entirely at the same time across the fleet. When taking into consideration this estimation, the new total weight will be 6,226.2 kg (calculated above), when multiplied by the amount of new seatbelts (30 %). The value, using TM, will be 1,867.86 kg whilst the total weight with AM will be 939.72 kg (a reduction of 50.31%). The sum reduction is a difference of 928.14 kg between the two manufacturing processes. According to the result of 928.14kg, the final weight in the case of only 30% of the total seatbelts being replaced would be 5298.06 kg (that is the difference between 6225.2 kg and 928.15). The total savings in fuel per year (using data from 2017 flights) will be 5, 934.6 tons, however when considering only 30%, the result that is obtained is 1 758,338 tons (The reduction of the total is from 11,796.02 tons to 10,037.72 tons). According to the research about *The rise of 3D-printing [1],* Vueling will save $2,285,979.4 of fuel per year and will avoid the pollution of an estimated 674.04 tons of CO2 (shown in Figure 38).

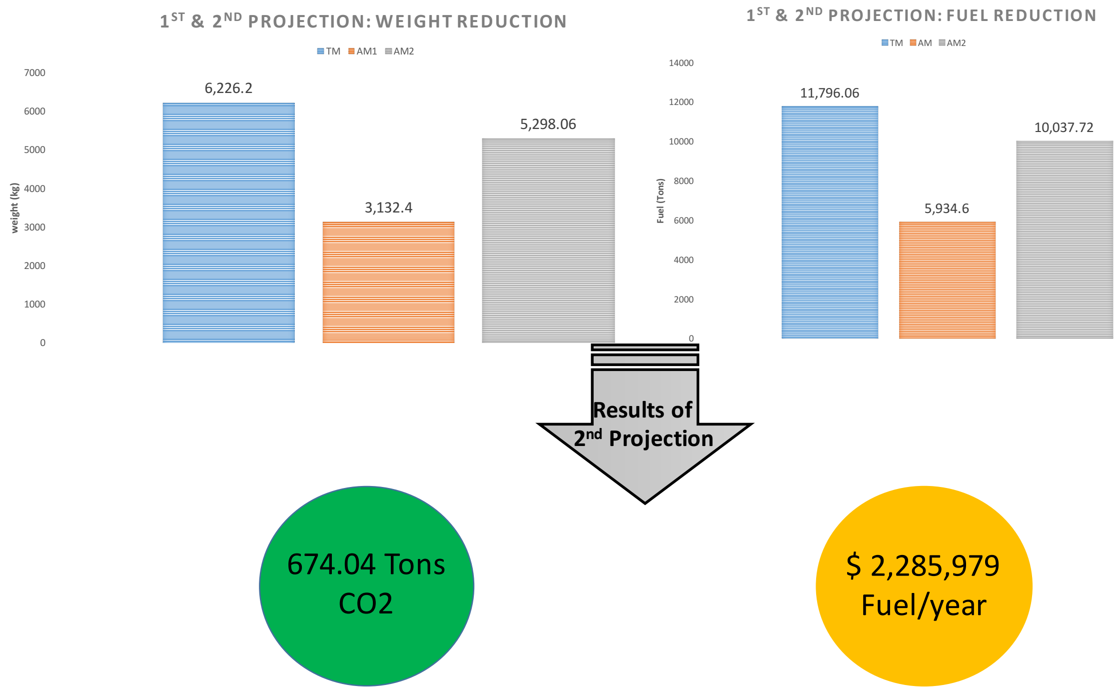


Figure 38.Summary of the 2nd Projection

5.4.3. Production cost of seatbelts with AM

In order to implement this technology, it is imperative to calculate what will be approximate total cost for the production of seatbelts with AM. Currently the cost of a seatbelt is around $ 114.07 [57] however, with AM it is necessary to calculate the cost of manufacturing with Ti6Al4V and PA 6/6. The price of Ti6Al4V, that is the part of the buckle and clasp, is around $ 378.138/kg [58] in this case, the weight of the total parts in titanium would be 66.23 g and the price for these first components would therefore be $ 25.04. The belt part, which will be achieved using PA 6/6 will require 84.7g ($ 75.98) as the price of the material is currently listed as $ 897/kg. This brings the total price of one seatbelt manufactured with AM to only $101.02, a reduction by $13.05.

The production cost of seatbelts with AM is cheaper than TM, however the airline would have to implement the 3D printer in its industrial plants. According to the above sections the type of printer utilised would be EBM. The price of this printer is not publically available, however it is possible to estimate using the webpage *3D insider* [59]. According to this website the price of industrial printers ranges from $ 20,000 to $ 100,000. The price of this printer is high due to its big size, however for the production of seatbelts the dimensions of the printer would not need to be a very high. As a result, a first approximation of the price would be around $ 50,000.

The initial investment is the price of EBM, but the certifications of EASA and FAA and the official CAD designs of the seatbelts are also required for manufacturing to begin. The certifications of EASA and FAA (see section 5.2 Traditional manufacturing of Model A) are the most expensive investment, the prices of which are not currently published. The price of the CAD design also has the same problem as the price of certificates. These two factors will be two constraints within the initial expenditure. However an educated estimation can be made for the prices of these constraints. These are available via the Commission Regulation (EC) No 488/2015 [19] in which some certifications within of aviation safety are estimated. The value that has been estimated for each certificate would be around $ 139,800.00 (as it is certificate that is the most expensive within Commision Regulations [19]). According to the section 5.2, the minimum certifications that Vueling should have will be five in total (ETSO-C22G, EASA C525-785, C535-561, EASA C21 and EASA AS8049). As a result, following the previous estimation, the expenditure for five certifications would be approximately $ 699,000.00. Regarding the price of the CAD design, CAD design software will be required, the price of which would be similar to AUTOCAD in which the price is $4.195.00 [20] and this has a maintenance yearly of $1,250.00/year [20]. As a result, the initial total expenditure using these estimations would be $ 753,195.00 (printer plus certifications and software CAD). Every year a maintenance fee will be required of $ 280,828.45 in the first projection (the second projection is $ 207,452.57) due to the maintenance required of CAD software and the safety certifications as well. Despite this estimation, it must be taken into account that the maintenance of certificates will be around four times less than the initial price estimate as it can be estimated that only 5% of the total seatbelts will be repaired annually. Table 10 presents a summary of the total expenditure, operation profits (benefits) and revenue to be calculated for the amortization.

Expenditure

Name	Units	Price/unit ($)	Total Price ($)
Printer	1	50,000.00	50,000.00
Certifications	5	139,800.00	699,000.00
Certifications Maintenance (25%)	5	34,950.00	174,750.00
CAD Design	1	4,195.00	4,195.00
CAD Maintenance	1	1,250.00	1,250.00
Number of seatbelts	1^{ST} Projection: 20,754 2^{nd} Projections: 6,227	101,02	1^{ST} Projection: 2,096,569.08 2^{nd} Projections: 629,051.54
Stock (1% of total)	1^{ST} Projection: 207 2^{nd} Projections: 62	101,02	1^{ST} Projection: 20,911.11 2^{nd} Projections: 6,970.38
Overall number of seatbelts	1^{ST} Projection: 20,961 2^{nd} Projections: 6,289	101,2	1^{ST} Projection: 2,117,480.22 2^{nd} Projections: 636,446.8
Seatbelts repaired (5%)	1^{ST} Projection: 1,038.8 2^{nd} Projections: 312	101,2	1^{ST} Projection: 104,828.45 2^{nd} Projections: 31,452.58
Total Expenditure		Overall number of seatbelt + CAD Design + Certifications + Printer	1^{ST} Projection: 2,870,675.22 2^{nd} Projections: 1,389,641.8
Total Maintenance		Certifications Maint + Cad Maint + Seatbelt Repaired	1^{ST} Projection: 280,828.454 2^{nd} Projections: 207,452.577

Operation Profits			
Name	**Units**	**Price/unit ($)**	**Total Price ($)**
Fuel saved/year	1	1ST Projection: 7,619,898.00 2nd Projections: 2,285,969.40	1ST Projection: 7,619,898.00 2nd Projections: 2,285,969.40
Vueling Operation profits in 2017	1	220,800,000.00	220,800,000.00
Total Operation Profit		Fuel save/year + Vueling Operation profit	1ST Projection: 228,419,898.00 2nd Projections: 223,085,969.00

Revenues

Name	Units	Price/unit ($)	Total Price ($)
Vueling Revenue in 2017	1	2,490,000,000.00	2,490,000,000.00

Table 10. Summary of Expenditure, Benefits and Revenues

According to two projections studied in previous section (shown in 5.4.1 and 5.4.2). The total investment is outlined below in different graphs in order to show the depreciation of these projections. The equation utilised to calculate the amortization is the following:

The equations to calculate the amortization would be the following:

$$
\begin{aligned}
D = \sum Operation\ Profit - \sum Expenditure \\
= \sum Operation\ Profit \\
- \sum Printer + Certifications + CAD\ Design + \#\ seatbelts * \frac{price}{unit}
\end{aligned}
$$

- Amortization of the 1st projection:

  According to the first projection (ideal condition) the total number of seatbelts that AM will be applied to will be 20,754 seatbelts (100% of the Vueling fleet). The expenditure of producing all seatbelts will be $ 2,1 M due to the price of one seatbelt with AM being $101.02 each unit and there is a stock of 1% of the total. The total expenditure then will be around $ 2.8 M According to the section 5.4.1 the total save of fuel yearly will be around $ 7,6 M. The total savings of fuel will be a profit that will not constitute as revenue. According to section 5.4 the total profits in 2017 was $ 220.80 M, the total savings would result in profits $ 228.42 M. These profits decrease when is applied the initial investment that is $ 2.87 M due to this investment, the operation profit will be $ 225.5 M. The revenue in

2017 were $ 2.13 B. Regarding the data of operation profit the years to obtain the amortization would be in the same year of the investment (shown in Figure 39). The maintenance will have $ 280,828.454 yearly

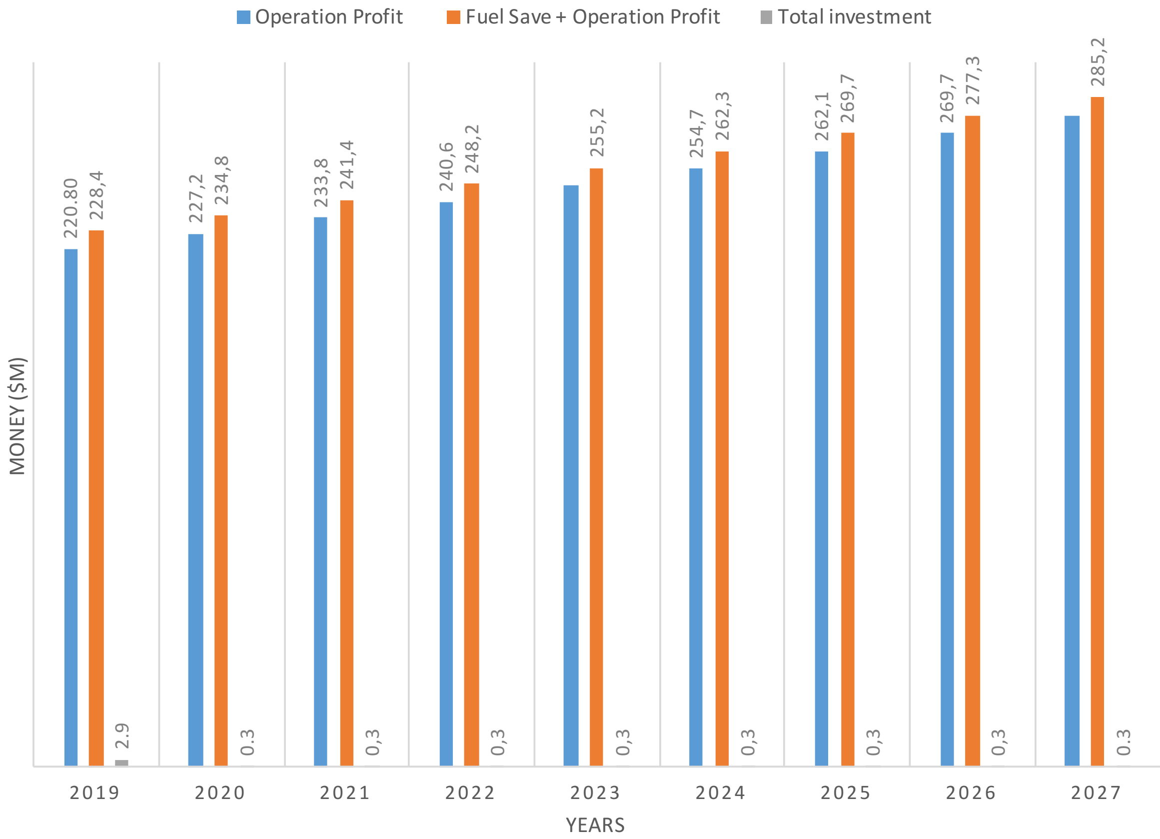


Figure 39. Amortization of the 1st projection

- Amortization of the 2nd projection:

However, the amortization of the 2nd projection (realistic condition), implementation of only 30% of the total seatbelts each year, would yield different results. The 30% of the total seatbelts of the Vueling fleet is 6,227 seatbelts. The expenditure to produce all seatbelts would be $ 636,446.8 due to the price of one seatbelt with AM being $101.02 each unit and there is a stock of 1% of total of 30%. The total expenditure will be around $ 1.39 M. According to the section 5.4.1, the fuel save will be around $ 2,28 M yearly that will be additional profit. Figure 40 depicts how the amortization of the total investment would be in the same year due to the expenditure being smaller than the projected profits.

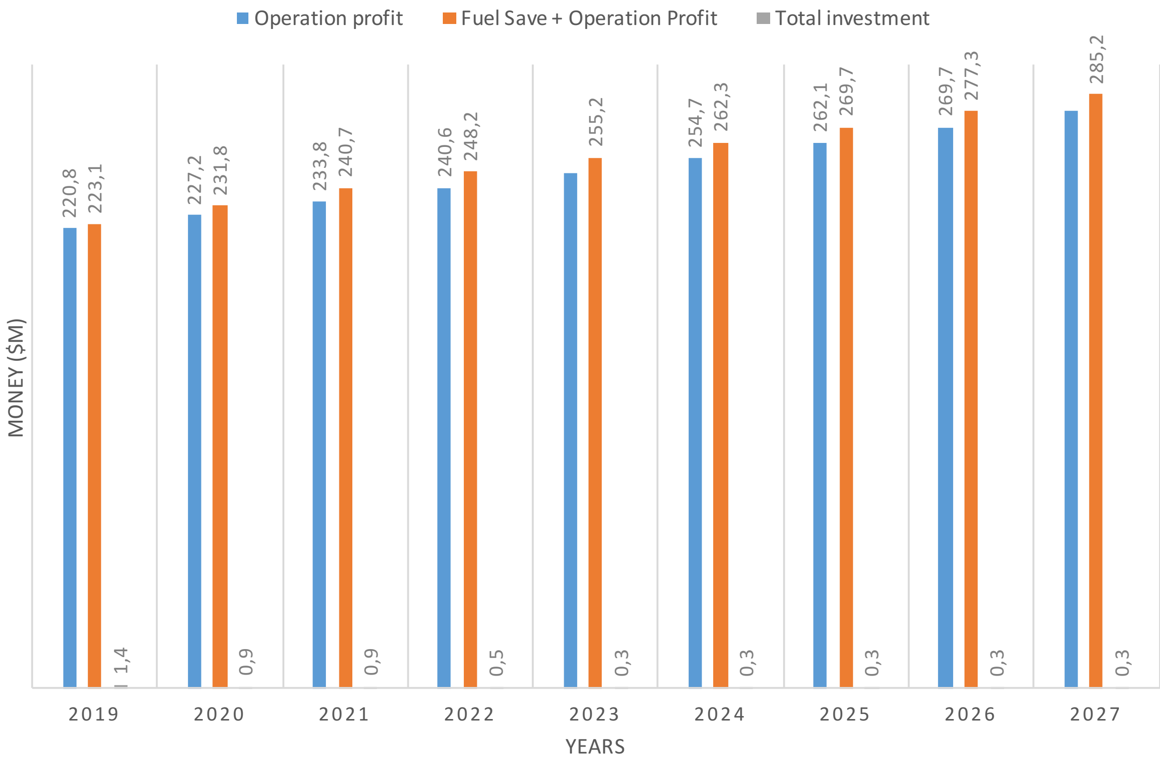


Figure 40. Amortization of the 2nd projection

5.4.4. Transformation of aeronautical supply chain

Due to the results obtained and conclusions made in the above section, additive manufacturing is suitable for the construction of seatbelts. This technology will also assist in improving diverse factors within an airline, such as fuel consumption and CO2. These are important factors that are integral to the progression of an airline (see Chapter 2 for Airbus´ goals for 2050), which could be improved by new technology such as AM. In the case that Vueling applies this new technology to its seatbelts, the supply chain[16] of the company would be changed. The aeronautical supply chain is currently made up of raw materials producers, manufacturers, suppliers and consumers (shown in Figure 41). The new supply chain would only be made up two distinctions, raw materials producers and consumers (in this case, Vueling). Vueling would only have the need for one EBM printer, the CAD Model of the model A seatbelt with the certifications of EASA and FAA and the raw materials in order to be able produce their own seatbelts without outsourcing (see Figure 42).

[16] Supply Chain is a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities involve the transformation of nature resources, raw materials, and components into a finished product that is delivered to the end customer.

Figure 41. Components of Aeronautical Supply Chain with TM

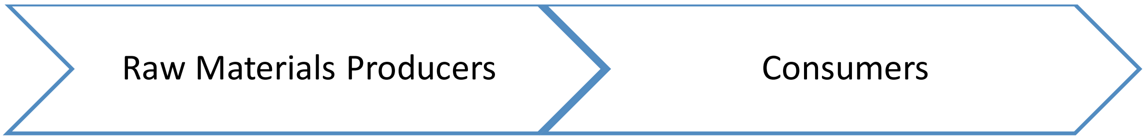


Figure 42. Components of Aeronautical Supply Chain with AM

The benefits of implementing AM in seatbelts would also be that seatbelt stock in the warehouse would be optimized with this technology and stock could be used and stored efficiently with minimal waste. According to Figure 43, a study realised by Deloitte [18], the production of cost with AM keeps constant irrespective of the amount of units produced. However, the production cost is reduced with the rise of pieces in the TM. In the case of seatbelts, the production will be small due to seatbelts not being replaced constantly. According to production cost of products, AM would be a better solution than TM due to it not needing any stock, therefore reducing the cost of production. Another benefit is that the lead-time would be reduced due to the supply chain being changed. A significant problem of aerospace industry is the lead-time of production which sometimes amounts to several months [61] with this technology that problem would be resolved. As of yet the buy to fly[17] is approximately 15-20 with this technology, production would be 1-1 [62] therefore the material utilised would also be without economic losses.

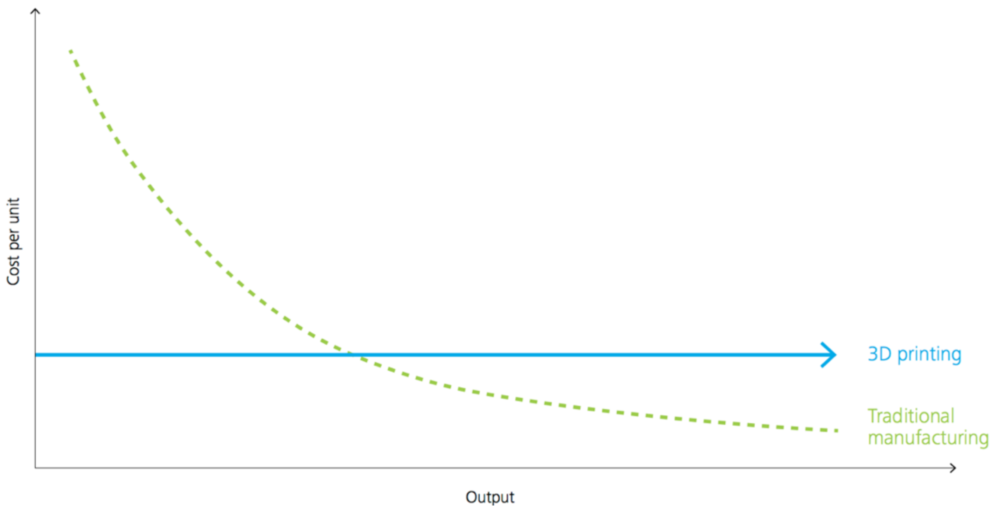


Figure 43. Cost Production of AM vs TM

[17] Buy to Fly is the weight ratio between the raw material used for a component and the weight of the component itself

CONCLUSIONS

The goal of this thesis was to assess the implementation of AM in the aeronautical field with a case study that focused on Model A (shown in section5.1) seatbelts. Before the implementation of this technology in an airline is possible, diverse studies needed to be conducted. This analysis was broken down into four parts. These parts were the identifying of current trends in the aeronautical field, the evolution of AM in the future, the applications most where it is most suitable to apply AM and the economic impact of AM in the manufacture of seatbelts. In the following sections the summary of results obtained will be outlined, including an analysis regarding results.

Results Obtained

In this subsection main results that have been obtained during this master thesis will be reviewed. The results are divided into the same parts that the project is divided into above.

Regarding the first study about the trends in the aeronautical field AM will be a technology implemented by the most important manufacturers such as Boeing and Airbus. Both manufactures are investing a lot of money in research about AM.

The second analysis covered the evolution of AM according to the Gartner Hype Cycle. AM will be utilised in a range of 5-10 years, however this graph and prediction was compiled in 2014, therefore the implementation of this technology will be in a range of 1-5 years from 2018.

The third part of study was the applications of AM. The seatbelts will be a good option for the application of AM. According to different research, the most suitable applications for AM would be the functional parts within items produced for use in the aeronautical field. As a result, in the case to apply AM is suitable to be implemented with AM.

The fourth study analysed models of seatbelts and concluded the model of seatbelt most suitable for this study is model A. The material for the production of the seatbelts would be TI6AL4V for the buckle and clasp and PA 6/6 for the belt. The total weight would result in a reduction of 50.31% in respect to traditional manufacturing. In terms of weight the seatbelts with AM would be around 150.93 g. This essay examined the airline Vueling specifically, in which two different projections were estimated (ideal conditions vs realistic conditions) in the application of AM. From these projections the total fuel that will be saved yearly and the tons of CO2 that would be avoided yearly were calculated.

In the first projection, the results obtained were that of a scenario with ideal conditions that would mean a reduction in weight of 3 093.8 kg between the two manufacturing processes. The reduction of fuel would be 5, 861.46 tons in 2017 and as a result $ 7 619 898 000 in fuel would be saved yearly. According to these results the pollution avoided would amount to 1185.95 tons of CO2 each year. From the initial investment, the first projection would be a depreciation of 0.5 years.

The second projection was the realistic condition in which the mathematical calculations were made in mind with the fact that only 30% of total seatbelts would be replaced. The results acquired with this calculation were that the weight would be decreased from 6,226.2 kg to 5298.06 kg. Regarding the fact that only 30% of total seatbelts would be replaced, the fuel save would be decreased from 11,796.06 tons to 1,758.338 tons. The replacement of 30% of the seatbelts would be made yearly, each year a saving of $ 2,285,979.4 in fuel would be achieved and a reduction in pollution would be around 679.04 tons of CO2. With this projection there would be an instant depreciation.

The price of seatbelts calculated with traditional manufacturing would be $ 114.07, however the price with AM would be only $101.02. Therefore the total saving from the investment of AM would be around $13.05 per seatbelt.

Finally, as a result of this analysis, it is clear to see that additive manufacturing has a lot of benefits to introduce into the aeronautical field, specifically, in the case of aircraft seatbelts. Some benefits that the thesis has proven is that from the optimization of the products, the lead-time would be drastically reduced and the buy-to-fly would be 1-1.

Analysis from results

This master thesis has demonstrated that AM will be a huge advancement in the aeronautical field. The implementation of this technology will be implemented within a range of 1-5 years from 2018. The investment of AM each day is of higher value in this field due to AM improving aircraft parts and the ease of customisation of aircraft components that is allowed with AM.

This thesis demonstrates that even with a small piece of aircraft being altered, many benefits can be obtained such as reduction of fuel or the reduction of weight, the most important benefit. These benefits will improve and influence the process of manufacturing and the improvement of materials utilised in pieces. Particularly as it is possible to apply this technology in other aircraft parts as GE [63] has implemented AM in pieces such as a fuel nozzle part.

Vueling would save money through the alteration of its aircraft seatbelts. Moreover, if this technology is implemented the problem of the time required to receive seatbelts would be eliminated (approximately one month) and Vueling would be able to optimize its warehouses and supplies.

Personal Evaluation

I began this thesis when I discovered the process of Additive Manufacturing as a variant of 3D printing with its diverse applications of printing including materials such as titanium. This intrigued me and I began to research about this new technology.

Despite my lack of knowledge, I knew that AM would make for an excellent study for my thesis.

Due to AM being a very new technology, research about large aircraft structures does not currently exist. As a result of this I made the decision to focus on a smaller but no less integral component of an aircraft, the seatbelt, despite the restrictive nature of date currently available.

This lack of data was also a motivation for the study as it also seemed the most appropriate to apply AM to a smaller component first, rather than larger aircraft parts. I sought the help of my professional contacts that work across a range of airlines for assistance in continuing with the thesis and they were able to provide me with details about airline seatbelts.

The most intellectually challenging parts of the project were the individual components of the seatbelts, the analysis and calculations that were required to decide their suitability for AM, particularly the clasp and buckle. I believe I have achieved interesting data and results that demonstrate the suitability of AM in aircraft component manufacturing, especially due to the benefits from the reduction in weight.

Evaluation of proposed goals

The realization of this thesis has been challenging due to the limited research of AM as it is not a technology that has already been widely implemented. As a result, it has to be taken into account the difficulty of obtaining suitable results and therefore their accuracy. However, all of the diverse goals proposed of in the initial abstract of this thesis have been completed. I am really pleased with the thesis regardless of the limitations that I found along the way.

Future work

The results that have been obtained are a first approximation of the consequences of implementing AM in an airline. The second step is to develop and achieve a prototype of the finished product. The prototype would be implemented with the materials and printer that have been chosen from this study (EBM). The CAD design would be able to be achieved using sophisticated design software such as CATIA. The continuation of this project would be to contact Vueling (or other suitable airline), a manufacturer and to apply the prototype and the materials in a few aircraft in order to obtain realistic results in a real and controlled environment.

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